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Using external focus (EXF) to direct attention externally toward the effect of movements on the environment leads to superior learning and performance compared to directing attention internally to body movements (internal focus, INF). However, the relationship between attentional focus strategies and non-attentional focus strategies, and task difficulty is unclear. The present study examined multiple theoretical frameworks to further understand these strategies. In Experiment 1, it was hypothesized based on the information theory that an EXF would be effective when individuals require conscious attention during more difficult tasks where a CON group would outperform when individuals' cognitive process is automatic during an easy task. In Experiment 2, the theories of variability were adopted, and it was hypothesized that an EXF would exhibit higher variability with greater performance, which indicates a more complex and adaptable motor control. In Experiment 3, subjective profiles were examined, and it was hypothesized that the EXF group would exhibit a higher competence, lower mental workload, and a fewer explicitly accessible knowledge, which reduces working memory load. Participants (*N* = 60) were randomly assigned to one of the EXF, INF, or CON groups and practiced a Fitts' reciprocal tapping task that varied in three task difficulties across two days. Two retention tests (5-minute and 48-hour) and transfer test (dual task) were conducted to measure the learning effects and the degree of automaticity. Our results showed that performance in both movement time and the number of errors improved, but there was no group effect on motor learning. The transfer test showed a

marginal effect with a medium effect size, showing that the INF group led to a greater number of error taps and a significantly increased performance variability than the CON group. The results of movement variability (SD and CV of the joint angular velocity) and time series variability (Sample entropy of joint angular velocity) showed SD increased with performance improvements, whereas CV and SampEn decreased. Group differences were not observed; however, an INF showed a marginal effect of having lower CV variability than the CON group in the transfer test. Changes in the subjective profiles (mental workload, perceived competence) paralleled the changes in performance with no group differences. However, the examination of explicit knowledge provided unique information. The EXF groups had a greater amount of explicit knowledge in the retention test. Additionally, investigating the types of explicit knowledge revealed that the INF group had a less proportion of knowledge about techniques, while the EXF had a more proportion of knowledge about techniques. To conclude, it is proposed that intervening motor execution with a cognitive process specific to body movements may drive individuals’ attention away from the task-goal, in turn reducing adaptable movement execution variability.

ATTENTION AND MOTOR LEARNING IN AN AIMING TASK

by

Masahiro Yamada

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Approved by

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To Ami:

Ami, I wouldn't have completed this dissertation without your love and support. You always cheered for me, encouraged me, and inspired me.

APPROVAL PAGE

The dissertation written by MASAHIRO YAMADA has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro

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CHAPTER I

INTRODUCTION

Statement of Problem

Directing an individual's attention to a certain cue has shown to affect motor performance and the learning of motor skills (Wulf, 2013). This conscious process of attention to internal or external cues is referred to as *attentional focus* (Magill, 2007). Attentional focus in Psychology, Motor Behavior and Sport Psychology has been studied for more than twenty years, and researchers have categorized various attentional focus strategies (Beilock, Wierenga, & Carr, 2002; Masters, 1992; Morgan & Pollock, 1977; Mullen & Hardy, 2010; Singer, 1986; Wulf, Höß, & Prinz, 1998). In 1998, Wulf et al. (1998) defined an external focus (EXF) as directing performers' attention to the effects of the movement on the environment and internal focus (INF) as directing attention to body movements and showed the beneficial effect of an EXF over INF in a ski-slalom and balance task. Since then, numerous literature replicated the EXF benefits in various motor skills (Wulf, 2013). The mechanism of this phenomenon is generally explained by the constrained action hypothesis (CAH) (McNevin, Shea, & Wulf, 2003; Wulf, McNevin, & Shea, 2001; Wulf, Shea, & Park, 2001), proposing that adopting INF disrupts the motor system, which results in a poorer performance, while EXF promotes a more automated motor system, which leads to an enhanced performance. More recently, the OPTIMAL theory has been proposed (Wulf & Lewthwaite, 2016) explaining that EXF decreases self-focus (*i.e.*, INF) while increasing the action-goal coupling, along with autonomy of support (*i.e.*, giving choices to learners) and enhanced expectancy (*i.e.*, positive perception toward the task being learned).

Most literature supports the benefits of EXF: 83% of the attentional focus literature in a balance task replicated the superiority of EXF (Park, Yi, Shin, & Ryu, 2015), and a meta-analysis favored EXF over INF (Kim, Jimenez-Diaz, & Chen, 2017). However, the CAH has been criticized for the lack of explanation of the attentional focus mechanism (Maurer & Zentgraf, 2007). This may be because the CAH explains the phenomena only from 1) motor learning specific to the external/internal focus of attention and 2) behavioral perspective. Regarding the first concern, Oudejans, Koedijker, and Beek (2007) suggested an application of a broader theoretical framework of motor skill acquisition to develop the understanding of attentional focus. For example, some of the predominant principles of general motor learning is the learning stage model, which stems from the information theory, and the dynamic system theory, which originated from meteorology, physics, and physics. Regarding the second concern, the external/internal focus paradigm has drawn conclusions based on performance outcomes or performance production measures. It is possible that we understand the mechanism of attentional focus motor learning in depth by examining individuals' cognitive aspects. Therefore, the purpose of this dissertation is to further develop the understanding of attentional focus instructions and motor learning from multiple theoretical frameworks.

Among various motor learning principles, one of the precedent theories of other contemporary theories is the information theory. This theory uses a machine analogous to explain human behavior by considering the "executive center" as the central processor unit. The executive center processes and integrates an input information (stimulus) and produces an output (response/behavior); thus, by examining a stimulus-response relationship the principles of motor learning can be understood (Schmidt & Lee, 2007). Some predominant theories that received a strong influence of the information theory are the three-stage of motor learning model (*e.g.*, Fitts & Posner, 1967) and dual process theory (Schneider & Shiffrin, 1977). The three-stage model explains the changes in the degree to which an online cognitive process (*i.e.*, conscious process) is required to perform a motor skill by practice (Fitts & Posner, 1967). The dual process theory (Shiffrin & Schneider, 1977) proposes a two process: a *controlled* and *automatic* process. Performing an easy, familiar, salient task requires a less cognitive process and the process is rather *automatic*; on the contrary, performing a difficult, novel, or unfamiliar task would require a large portion of attention to the task and the process is rather conscious (controlled) (Schneider & Shiffrin, 1977). For example, identifying a crosshair from hundreds of circles is easy and the stimulus is salient. As a result, an automatic process is used and the expected reaction time for decision making is fast. Accordingly, picking a hexagon from hundreds of octagons requires a conscious process because it is more difficult. The example provided here represents an absolute aspect of task difficulty (*i.e.*, finding salient information is "easy" regardless of individuals). However, it is important to note that the process is flexible. With practice, a controlled process becomes more automatic. Here, the difficulty of a task is relative (Logan, 1985) (*i.e.*, after practice, a difficult task becomes easier). In the present study, it is hypothesized that applying this concept of motor skill learning and performance would explain the inconsistent attentional focus effects by task difficulty (Landers et al., 2005; Wulf et al, 2007).

While the cognitive process theories and attentional focus research are not completely separated paradigms considering the origins of these theories, there is another emerging theory in motor behavior that is outside these areas. The theoretical basis of this theory is variability. Traditionally, variability has been considered (at least based on the information theory) as noise (*random* deviations from general performance) since human movements and complex systems are far from perfect (Slifkin & Newell, 1998). However, different theories have been proposed that variability is *not* random noise and motor skill proficiency can be observed in the differences and changes in variability (Bernstein, 1967; Thelen, 2005; Verejiken, van Emmerik, Whiting, & Newell, 1992). While one approach to examine variability is to examine standard deviations from the mean of performance, a recent theory called the nonlinear dynamics theory has examined *time series* variability as trial-to-trial fluctuations. This approach has revealed that there is a clear distinction in trial-to-trial fluctuation pattern (*i.e.*, fluctuations of stride length of hundreds of steps; intervals of heart beats) between healthy younger adults and older adults (Grabiner, Biswas, & Grabiner, 2001). More interestingly, this time-series variability can reveal a "hidden" structure of fluctuations that cannot be captured by performance mean and its standard deviation (Newell & Vaillancourt, 2001). Recently, researchers have adopted this approach in the EXF/INF paradigm by assessing the relationship between variability of different joints (Fietzer, Winstein, & Kulig, 2018; Lohse, Healy, & Sherwood, 2014; Vidal, Wu, Nakajima, & Becker, 2018) or time-series variability (Diekfuss, Rhea, Schmitz, Grooms, Wilkins, Slutsky, & Raisbeck, 2018; Rhea, Diekfuss, Fairbrother, & Raisbeck, 2019; Vaz, Avelar, & Resend, 2019). Currently, however, there is no consensus regarding how attentional focus affects variability and time-series variability. To understand the cause of these inconsistencies, more work is imperative (Vaz et al., 2019).

Additionally, there is little knowledge about the effect of EXF and INF on the learner's perception and cognition. Previous research has shown that subjective mental workload was affected by motor proficiency and task difficulty (Shuggi, Oh, Shewokis, & Gentili, 2017), which was assessed by NASA-Task Load Index (NASA-TLX) (Hart & Staveland, 1988). However, only a few studies have examined the relationship between attentional focus and mental workload (*e.g.*, Diekfuss, Ward, & Raisbeck, 2017). Moreover, compliance checks and perceived competence have been adopted in motor learning research (Frikha, Chaari, Elghoul, Mohamed-Ali, & Zinkovsky, 2019; Marchant, Clough, & Crawshaw, 2007; Porter, Nolan, Ostrowski, & Wulf, 2010). Studies have shown that perceived self-competence was dependent upon the type of augmented feedback (Frikha, et al., 2019) or task difficulty (Fredenburg, Lee & Solmon, 2001); compliance checks have been described merely as a confirmation of the provided instructions (Marchant et al., 2007; Porter et al., 2010). It is possible that learners' perception adds more explanation for the development of the attentional focus mechanism. Therefore, it is imperative to assess the effect of attentional focus instructions on mental load, compliance, and perceived competence in motor learning.

Although the subjective workload would provide useful information to explain the mechanism of attentional focus in depth, it lacks in a theoretical explanation. To supplement this limitation, the present study will also examine the changes in the memory structure by examining explicit knowledge from theories of memory. According to Masters (1992), the memory system is known to shift from explicit (verbalizable memory) knowledge to implicit (non-verbalizable memory) knowledge as individuals learn motor skills. Research shows instructional strategies that promote accumulation of explicit knowledge are detrimental especially under pressure or during a dual task procedure (Koedijker, Oudejans, & Beek, 2007; Masters, 1992; Poolton, Maxwell, & Raab, 2006). Poolton et al. (2006) suggest that performance decrement by an INF may occur due to the accumulation of explicit and implicit knowledge rather than the constrained motor system. Although the structure of memory still relies on subjective report, we believe that this testable hypothesis with other subjective variables that may affect the difficulty of task and motor learning (*e.g.*, mental workload and perceived competence) would further develop the theory of attentional focus and motor learning.

Existing literature has been relatively clear regarding the EXF benefits in motor performance. However, there are also inconsistent findings showing no effect between EXF and INF (*e.g.*, de Bruin, Swanenburg, Betschon, & Murer, 2009; Lawrence, Gottwald, Hardy, & Khan, 2011; De Melker Worms, Stins, van Wegen et al., 2017a). It is unclear whether these contradictory findings are due to methodological issues, natural consequences that are statistically expected, or due to other variables that moderated the effect of an EXF or INF. This warrants further investigations to understand the effect of attentional focus strategies on the learning of motor skills from multiple perspectives.

Objective and Hypothesis

The primary objective of the present study is to investigate the effect of attentional focus instructions in a motor skill from multiple theoretical approaches to develop the understanding of attentional focus effects.

Aim 1: To determine the influence of practice and different task difficulty on the EXF/INF instructions by applying the general motor learning model (Fitts & Posner, 1967). Participants will be randomly assigned to one of the EXF, INF, or CON groups and practice three different task levels of a reciprocal Fitts' task.

Rationale of the hypotheses below is that performing an easy task (*i.e.*, low Index of Difficulty, ID_{low}) will require little attention to perform the task. Therefore, not directing attention to a specific cue about the task (*i.e.*, "do your best" or CON) would be more effective than directing individuals' attention to the task (*i.e.*, EXF and INF). On the contrary, when the task is too difficult (ID_{high}), participants will be preoccupied with simply performing the task, and thus provided instructions (EXF or INF) will be ignored, and there would be no difference between conditions. Therefore, an EXF benefit will lie in a moderately difficult task (*i.e.*, ID_{med}) relative to an INF or CON when it requires some portions of attention to the task but has some mental room to utilize a provided instruction. Further, since cognitive process shifts from more conscious to automatic process, a difficult task would subjectively be less difficult. For the present study, learning will be inferred as performance during the retention and transfer tests. The dependent variables (performance outcomes measured as the velocity of movements) will be analyzed. The effect of practice will be measured with a repeated measure of ANOVA between the baseline and retention tests. Further, a transfer test using a dual task procedure will examine the automaticity of the motor skill. The main hypothesis for the practice effect is:

> ***Hypothesis 1a: There will be effects of a three-way interaction between Instruction, ID, and Time***—During practice, compared to the baseline, the EXF group will perform better than the INF and CON groups in the ID_{med}, the CON will perform better than the INF and EXF in the ID_{low}, and there will be no difference between the groups in the ID_{high}. However, due to the shifts in cognitive process by practice, the most difficult task would subjectively become moderately difficult, moderately difficult task would subjectively become easy. As a result, the EXF group would perform better in the ID_{high} in the retention tests, and the CON group would perform better than the EXF and INF in the ID_{low} and $_{med}$.

For the dual-task cost in the transfer test:

> ***Hypothesis 1b***: ***Dual-task cost during the transfer test***—The dual-task cost will be lower in the EXF group to the INF and CON group. Also, higher ID conditions will result in the higher dual-task cost. The dual cost will be significantly lower in the EXF group in the high and medium ID's, where no difference will not be evident between the EXF and CON groups in the low ID.

Aim 2: To understand the mechanism of attentional focus from the perspective of variability. For the present study, movement variability is measured as coefficient of variance (CV) of angular velocity at shoulder, elbow, and wrist joint. Time series variability is measured as sample entropy (SampEn) of angular velocity at the shoulder, elbow, and wrist joints. These variables will be analyzed with a repeated measure of ANOVA during the testing phase.

The rationale for the following hypotheses is that Verejiken et al. (1992) showed gradual increase in variability (as SD) of joint angles in a ski-slalom simulation task (*i.e.*, releasing the degree of freedom), which supported that movement variability changes through learning motor skills. Rhea et al. (2019) showed that a nonlinear method may reveal meaningful information that general variability cannot. Specifically, Rhea et al. found a greater SampEn in the EXF condition than the INF where no difference was found in SD in a postural control task (standing still). However, Diekfuss et al. (2018) and Vaz et al. (2019) found a decrease in sample entropy in a dynamic balance task with practice. Vaz et al. (2019) suggested that whether the optimal entropy is high or low is dependent upon task dynamics. For fixed-point attractor dynamics (*e.g.*, static balance), a reduction in entropy may indicate non-optimal while a task with a cyclic (*e.g.*, walking) attractor dynamics may present the reduction of the entropy as optimal. In a reciprocal aiming task, the distal joint (*i.e.*, wrist) should provide a fixed pattern for a constant performance while proximal joints (*i.e.*, elbow and shoulder) provide cyclic patterns of limb back and forth between two targets. If the release of the proximal joint variability leads to a reduction of performance variability (Bernstein, 1967; Fietzer et al. 2018) and it indicates more adaptable behavior, the complexity of time-series variables (SampEn) may also be joint-specific. Verejiken et al. (1992) adopted SD as a movement variability measure. However, the range of SD changes based on the unit. Therefore, in the present study, we adopt the proportion of variability as coefficient variation (CV) to compare variability between different joints. Therefore, the present study will examine angular displacement of CV and angular velocity of SampEn at shoulder, elbow, and wrist joints. As such, the primary hypothesis of the present study for practice effects are:

Hypothesis 2a: ***Learning effects for movement variability***—Movement variability as CV of the angular displacement will be higher in the retention tests compared to the baseline. However, the EXF group will have a higher variability than the INF group.

Hypothesis 2b: Learning effects for angular velocity variability as SampEn—SampEn will be lower in the distal joint than the proximal joints and the variability will be higher for lower ID's compared to the higher ID's (*i.e.*, two-way interaction). Also, the EXF will exhibit a higher SampEn at the proximal joints than the distal joint compared to the INF and CON groups.

Hypothesis 2c: ***Transfer effects***—Directing attention away from the task in the transfer test will cause an increase in CV and SampEn. However, the EXF will exhibit a lower entropy at the proximal joints (*i.e.*, shoulder and elbow joints) and higher entropy at the distal joint than the INF and CON groups in the later stage at the proximal joints (interaction effect).

Aim 3: To determine the effect of attentional focus strategies on the subjective profiles: memory structure as explicit knowledge, mental load, magnitude compliance, and perceived competence in relation to performance. The rationale of the following hypotheses is that subjective mental workload has been shown to increase with task difficulty (Shuggi et al., 2017), and an EXF has shown to promote an efficient performance under a dual-task procedure, suggesting that it consumes less attentional resources (Kal et al., 2013; Wulf et al., 2001). Therefore, an EXF is predicted to have a lower subjective workload than the INF. Similarly, there is a relationship between proficiency and task difficulty in perceived competence (Frihka, et al., 2019; Fredenburg, Lee & Solmon, 2001). Thus, an EXF benefit may be further explained due to an increase in perceived competence. Regarding the compliance, some studies showed the magnitude of compliance was significantly different between EXF and INF (Lohse et al., 2014; Raisbeck et al., 2020). This may explain the inconsistent findings (deBruin et al., 2007). That is, at the initial stage of learning, participants may not comply with a provided instruction until they gain some familiarity in performing the task (Wulf et al., 1999). Regarding explicit knowledge, teaching strategies have been shown to affect implicit and explicit knowledge formation during motor learning (Green & Flowers, 1991; Kodejiker et al., 2007; Masters, 1992). In the present study, the number of thoughts provided by participants' reports is counted across various time points. This will examine how explicit knowledge influences motor skill learning and whether the memory structure is affected by attentional focus. Our additional interest is the type of explicit knowledge. Qualitative research has shown that performers have a variety of attention that can be categorized in many ways (Bernier et al., 2016; Raisbeck, Yamada, Diekfuss, 2018). Thus, the type of explicit knowledge will also be examined. To examine the effect of attentional focus on the subjective profiles in learning an aiming task, the following results will be hypothesized:

Hypothesis 3a: ***Number of explicit rules during the acquisition phase***—There will be no difference between the groups in the initial stage. All groups will gradually increase the number of rules. However, it will decrease with further improvements (due to shift to implicit knowledge). The INF group will have a higher amount of explicit knowledge than the EXF and CON groups. Further, a greater amount of thoughts will be expected for the higher difficulty than than the lower ID's.

Hypothesis 3b: Mental workload during the acquisition phase—The score of the mental workload assessed by NASA-TLX will be higher in the high ID than lower ID's. However, mental workload will decline as participants become more proficient (*i.e.*, in the later stage of learning). There will be no difference between the groups in the initial stage (*i.e.*, the baseline and first block of the acquisition); however, the EXF group will exhibit lower mental workload scores than the INF and CON relative to the baseline.

Hypothesis 3c: Compliance—The magnitude of compliance (score) will be higher in the later blocks than the first block regardless of groups. The score will be higher in the lower ID than higher ID's. The magnitude of compliance will be higher in the EXF group than the INF group during the retention tests, and both groups will be higher in the retention tests than the transfer test. There will be no difference between groups during the transfer test.

Hypothesis 3d: ***Perceived competence***—The score will be higher in the later stage than the initial stage. The score will be higher in the low ID than the higher ID's. In the later stage, the EXF group will exhibit a higher score than the INF and CON.

Limitations and Assumptions

1. Performance differences are due to the dependent variables: provided verbal instructions, time, and task difficulty (*i.e.*, different ID's)
2. Participants prior to participation in the study are naive to the task, and thus considered as "novices."
3. Performing the task with participants' non-dominant hand would increase the chance of making the task more novel.
4. The task will have a practice effect: Participants will become better as they practice the task during the acquisition phase.
5. Retention tests will reflect the learning effect.
6. Dual-task procedure during the transfer test will reflect the degree of automaticity of the practiced skill.
7. There will be attentional focus effects in the given task.

8. Increasing Index of Difficulty increases performance error or decreases movement speed.
9. Random assignment of groups will consolidate some individual differences.
10. The cohort recruited in the study will be generalized to the population that has the same criteria.
11. Participants will not practice the task outside the laboratory.
12. Participants will perform the task with maximum effort.
13. Participants will understand and follow given instructions.
14. Participants will honestly answer questionnaires.
15. By conducting the experiment at the same location, similar lighting system, similar temperature, participants will have minimal influence of environmental factors.

Operational Definitions

Attentional focus: What performers are consciously paying attention to or thinking about.

External focus (EXF): Directing attention to the effects of the movement on the environment.

Internal focus (INF): Directing attention to body movements.

Control group (CON): Participants who receive only the goal of the task and are free to vary their thoughts and attention during practice.

Retention test: A test that will be held outside the working memory, and thus represents long-term memory or learning effect of motor skills based on experience from the experimental procedure.

Transfer test: A test with a secondary task, which measures the theoretical cognitive load.

Variables

Independent Variables

Instruction/Group: Participants will be randomly assigned to one of the EXF, INF, or CON groups.

Time: Baseline, blocks during the acquisition phase, 5-minute delayed and 48-hour delayed retention, and transfer test phases.

ID (Index of Difficulty): Task difficulty is manipulated by changing the distance and size of the targets.

Dependent Variables

Movement error: The center of the target to the center of object as a mean radial error (MRE).

Movement consistency: Variability of performance as a bivariate variable error (BVE).

Movement Time (MT): The number of hits divided by the duration of each trial (*i.e.*, 30sec)

Number of error taps: The number of times that participants hit outside the target areas.

Psychological profiles: The total scores of the NASA-TLX divided by the number of items, the magnitude of the compliance check in the 7-point Likert Scale, the number of explicit rules, and the scores of the perceived competence questionnaire in the 7-point Likert Scale.

Movement complexity: Measured in sample entropy of angular velocity.

Movement variability in the coefficient variance (CV): The measure of the standardized standard deviation represented by SD/M.

CHAPTER II

REVIEW OF THE LITERATURE

Overview

Successful motor control is the foundation of functional independence since our daily life develops according to the premise that we can accurately execute motor skills such as eating, typing, and commuting (*e.g.*, walking and driving). Losing these abilities due to aging or pathologies makes our society vulnerable. To this end, understanding and developing the science of motor behavior is imperative. The following literature review will begin with defining some critical terms of motor control, learning, and performance variables. Next, the fundamental theories of motor control and motor learning will be briefly introduced. Then, motor control theories and motor control models specific to goal-directed aiming tasks will be discussed. In the following section, a new paradigm that has emerged outside of cognitive and experimental psychology—degree of freedom problem and dynamic systems or nonlinear dynamics theory—will be introduced. Finally, theories of attentional focus will be discussed, followed by the gaps in the existing literature and discussions of the preliminary findings and limitations that lead to the present dissertation work.

Skills and Motor Learning

When muscles concentrically, eccentrically, or isometrically contract and overcome internal and external inertia, a movement occurs. Muscle contractions can happen for various reasons. When we consider motor control and learning, we mean “motor skills” rather than simply movements. Motor skills are defined as 1) voluntary, 2) goal-directed, and 3) learned tasks (Adams, 1987). Thus, reaction time, movement time, and anticipation in response to a stimulus, or any “willful” movements are skills, while twitches and reflexes are not skills since they are involuntary and inherent. Motor skill “performance” is influenced by various factors. A relatively good performance in a dart throw may be due to the proficiency of the performer or simply luck. The latter does not represent the thrower’s average performance; similarly, mental or physiological fatigue may negatively affect the quality of performance. Trial by trial performance may or may not reflect the performer’s general proficiency. In contrast, motor “learning” is defined as “a relatively permanent change in behavior, or behavioral repertoire, that occurs as a result of experience” (Terry, 2006, p.5) and is not influenced by performance variables (Magill, 2007). However, learning is not directly observable and rather can only be inferred from observable behavior (Magill, 2007). Therefore, learning is inferred from performance outcomes in the retention test where performers are tested outside the duration limit of working memory (i.e., approximately 20 seconds) (Adams & Dijkstra, 1966).

Performance can be observed by outcomes or movement coordination patterns. Regarding motor skill improvements, Magill (2007) introduced five characteristics: as individuals learn motor skills, performance becomes better, demonstrated by increasing scores or decreasing errors (i.e., *improvement*); performance variability progressively decreases (i.e., *consistency*); consistency lasts over a longer period of time (i.e., *persistency*); performance becomes stable and more resistant to external or internal perturbations (i.e., *stability*); and individuals become able to perform under various situations (i.e., *adaptability*). Performance is usually expressed as the mean of performance outcomes; consistency is measured as standard deviation (SD) of the mean; and stability and adaptability can be measured via a dual-task procedure, which performers simultaneously perform two skills, or via a transfer test, which performers are tested in a different context from the practice environment.

Theories of Motor Control and Learning

When these performance characteristics are observed for hundreds and thousands of trials, motor learning takes a lawful pattern called "Power Law." Introduced by Snoddy (1926) and popularized by Crossman (1959), it has been used as an indicator of motor learning. When performance outcomes were plotted into a log-log plot—logarithm function of trial numbers in x axis and logarithm function of performance on y axis—motor skill learning takes the linear path (Figure 2.1).

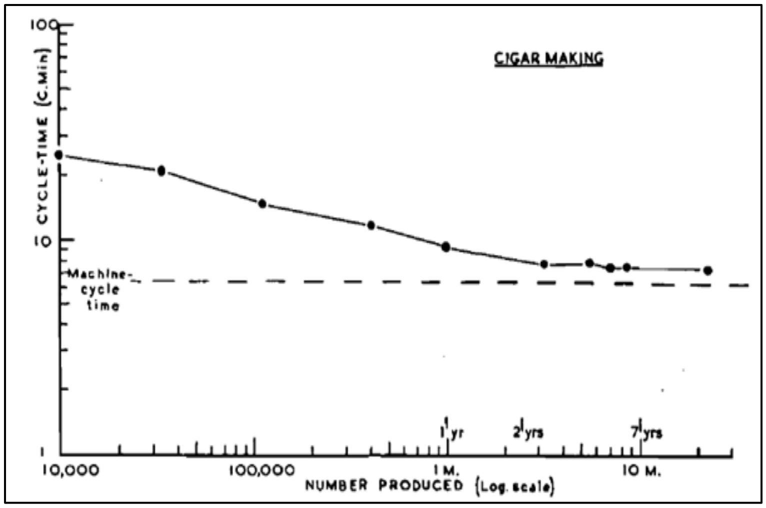


Figure 2.1. Logarithm Linear Relationship of Motor Skill Learning. Retrieved from Crossman (1959). A theory of the acquisition of speed skill. *Ergonomics, 2*(2), 153–66.

This indicates that the rate of improvement at the initial stage is rapid and the gain of the same unit of improvement takes log(n) practice trials. This law was recently replicated and accepted as a general law of motor learning (Stratton, Liu, Hong, Mayer-Kress, & Newell, 2007). Logan (1988) described that any motor skill acquisition that does not fit in Power Law is not motor learning. Thus, Power Law shows a pattern of performance improvements through practice. However, Power Law does not explain how individuals interact with the environment and learn to improve motor skills. The following sections will discuss different theories explaining the mechanism of motor learning.

Information Processing and Attention

Both improvements and the learning of a motor skill requires a complex coordination of our limbs while interacting with the environment. Traditionally, researchers have borrowed the analogy of a computer algorithm to explain the mechanism of how we interact with the environment and produce a complex movement

(Thagard, 2005). This is called the “information processing theory” and has served as the infrastructure for many motor learning and attention theories. Most motor learning theories, from the learning stage model by Fitts and Posner (1967), to Fitts Law (Fitts, 1954: Fitts & Peterson, 1964), are all based on this theory. The term, “information,” in the context of this theory is defined as the number of uncertainty that can be decreased by its half: $H = 1/P_i$, where H represents the amount of information and P represents the probability that will occur under a given event(i) (Attneave, 1959). Thus, H = 1 means that there are two alternatives, and it requires one bit of information for an absolute certainty. Similarly, H = 4 means there are 16 alternatives, and thus takes 4 bits to decrease the uncertainty to its complete certainty (16 to 8 to 4 to 2).

We receive information from our senses (i.e., input or perception). This information is processed, integrated by the controller, or the “executive center,” and an intended movement is produced (i.e., output or action). These distinctive stages of processing are (1) Stimulus identification, (2) response selection, and (3) response programming (Schmidt & Lee, 2005). The underlying assumption of the information processing theory is an input to the system is processed in a serial manner (Figure 2.2):

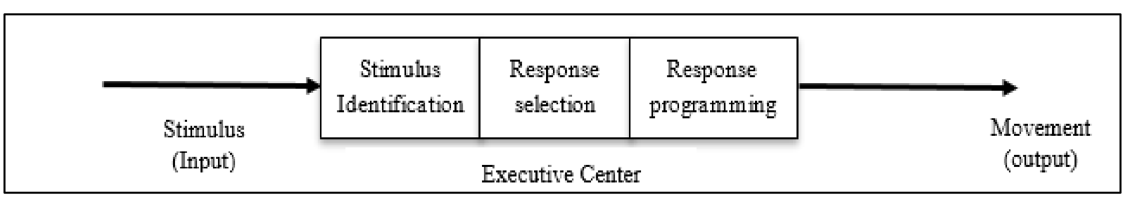


Figure 2.2. Information Processing Stages. Adapted from Schmidt, R.A. & Lee, T. D. (2005) *Motor control and learning: A behavioral emphasis* (4th ed.). Champaign, IL, US: Human Kinetics.

The central questions of the information processing theory are to identify what information is processed at which stage and factors that limit or facilitate processing that information. If we know, for example, 2 and 3 are entered and the output is 5, then it was due to the addition of the two and three that led to the output of five. By understanding inputs and processes, we understand the output (action), and thus we unravel how we interact with the environment. This logic is called “reductionism.” Researchers have tested these questions by introducing inputs as auditory, visual, or sensory stimuli and examining the output as a reaction time (RT). RT is defined as the time it takes from the introduction of a stimulus to the initiation of the response, which is considered as the time it took to process the input to program the output (Magill, 2007).

Historically, researchers extensively examined this perception-action relationship from the information process theory to reveal the mind: RT becomes faster (i.e., information is processed faster) with auditory and tactile information than visual information; RT is faster as clarity (i.e., how well-defined the stimulus is) of visual information increases; and RT is also faster as intensity (*e.g.*, brightness and loudness) of information increases (Schmidt & Lee, 2005). Additionally, when stimuli are presented through multiple sensory modalities, RT has shown to improve, which is known as intersensory facilitation (Schmidt, Gielen, & van den Heuvel, 1984). Other primary questions were, “how is information identified and processed?” or “what factors are processing of information influenced by?” These questions have been studied in the psychology of attention. “Attention” can be defined as concentration of mental activity that permits processing limited information out of vast information from the sensory systems (external environment) or memory systems (internal environment) (Maltin, 2008). Research in this paradigm has a premise that our attention is limited. This premise is consistent for any attentional theory that does not even adopt the information processing theory (*e.g.*, Khan, 1973 as an attentional resource theory). Because of this limit, researchers have examined dividing attention to different internal or external environments (*e.g.*, Strayer, Drews, & Johnston, 2003; Wikman, Nieminen, & Summala, 1998) or selectively directing their attention to a certain cue (*e.g.*, Conway, Cowan, Bunting, 2001; Moray, 1959; Treisman, 1964; Wood & Cowan, 1995).

The primary interest of the early attention studies was how and where the input is identified. Welford (1952) showed delaying two stimuli allowed subjects to respond to both stimuli, but subjects were not able to respond when the interval between the two stimuli was too short. This study suggested that humans require some time to process a stimulus (i.e., refractory period), and that information is “filtered” and processed one by one. Cherry (1953) adopted a technique called dichotic listening, which subjects hear one information from one ear and another information from the other ear. In that study, subjects were not able to remember unattended information. However, subjects were able to detect the physical properties of the information like the volume of the sound. Broadbent (1958) proposed that some information can be processed in parallel, but a filtration occurs at an early stage; following this stage, information is further processed in a serial manner (i.e., bottleneck). Later, familiarity of information is found to attract attention (Treisman, 1964), or a novel event (in the visual field) is found to draw attention (Cole, Gellatly, & Blurton, 2001) even if this information was not attended.

Thus, information processing was found to be more flexible depending on the properties of information. That is, some information is attenuated (to be ignored) or amplified (to be more salient) to be or not to be processed (Treisman, 1960). Later, other researchers suggest that information filtration occurs at later stages (Norman, 1969). More recently, information processing is dependent upon working memory load, called "Load Theory" (Lavie, Hirst, de Fockert, & Viding, 2004), just like picking out a baseball from basketballs requires a low working memory but finding a women's basketball among men's basketballs requires more working memory. These studies have revealed why some stimuli draw our attention, why we overlook seemingly obvious information, and the factors influencing information processing and attention.

After a stimulus is identified, individuals need to decide a correct response, which is the response-selection stage. This stage has been extensively studied in the stimulus-response (S-R) paradigm. In this paradigm, Hick (1952) and Hyman (1953) are two well-known researchers who found a lawful pattern. They found the logarithm (of base 2) linear relationship between the number of alternatives and RT, known as "Hick's Law" or "Heyman and Hick's Law," suggesting that RT increases as the number of choices increases. Another important finding was the S-R compatibility or incompatibility, which laid the foundation of numerous theories in different disciplines. The S-R compatibility examined the effect of association between a stimulus and the response. For example, Fitts and Deininger (1954) found that RT slowed as the "naturalness" of the association between the S-R decreases. That is, when a stimulus is a right arrow and the required response is to tap on the right target, the stimulus and response are compatible. S-R incompatible means a stimulus is showing a left arrow, but participants are asked to respond to hit the right target. Figure 2.3 shows another example of an S-R incompatible design.

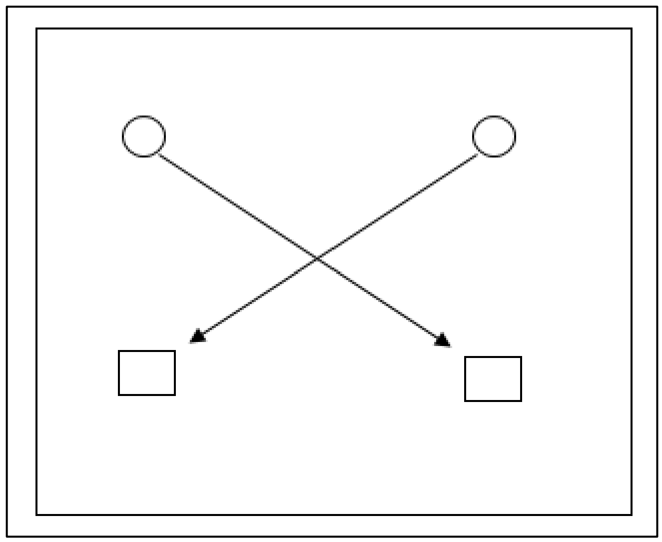


Figure 2.3. A Classic S-R Incompatible Situation. Circles represent Stimulus lights and squares represent Response buttons. During the S-R incompatible condition, participants are asked to press the right button when the left stimulus turns on.

The S-R compatibility is consistent for different sensory modalities. For example, an auditory S-R compatibility research showed that hearing a quiet sound to exert a weak force as a response (i.e., S-R compatible) resulted in faster RT relative to hearing a louder sound to exert a weak force (i.e., S-R incompatible) (Romaiguere, Hasbroucq, Possamai, & Seak, 1993). Further, RT in response to hearing the word “right” or “left” to press the corresponding button depends on the side of the ear that participants hear from, which is known as Simon effects (Simon & Rudell, 1967).

The last stage of information processing is the response-programming stage. In this stage, some of the programming may require accessing the long-term memory and preparing activation of corresponding motor system, called feedforward or tuning (Schmidt & Lee, 2005). A lot of motor learning and attention theories propose the mechanism of how this memory representation is made, strengthened, and discarded to improve motor skill acquisition. Henry and Rogers (1960) proposed the "memory drum theory," proposing that programming of an output requires tapping "neuromotor memory," just like how a computer will access its drum memory; logically then, retrieving a larger amount of information requires a longer time, and thus RT would be longer for a more complex movement. Henry and Rogers tested three different movements and showed that RT was longer for a more complex movement relative to a less complex movement. Later, this study was criticized since (1) one of the three tasks required accuracy where two others were not and (2) the duration to complete each task was different (therefore, RT may have been longer simply due to this difference); as a result, the theory was turned down (Schmidt & Lee, 2005). However, the notion about neuromotor memory and Henry's thoughts about information processing and motor coordination are still valid.

Learning as Information Processing

While the development of theories by empirical evidence is important, it is also important to consider a more global conceptual framework to apply these theories to practice. One of the most accepted learning models in motor learning is Fitts and Posner's three stage learning model (1967), which developed from the information processing theory. According to Fitts and Posner, individuals' cognitive processes change throughout learning of motor skills. The first stage is the cognitive stage in which individuals pay a large proportion of conscious attention to perform a motor skill and engage in a lot of problem-solving processes regarding "what to do." Fitts and Posner explain attention during this stage such as kinesthetic and visual information about arm or leg positions, would be ignored in the later stage. In the second stage called the associative stage, individuals make associations between stimulus and response (i.e., what to do in response to a specific situation). This stage is characterized with larger errors but less than those of the cognitive stage, and individuals learn how to perform the skill better. The last stage is the autonomous stage, which is characterized with less cognitive process and interference from the environmental conditions. Due to tremendous amount of practice, conscious process is no longer necessary and thus performing the learned skill becomes automated.

An important component in this model is that the model is based on adults learning. Fitts and Posner (1967) explain most skills have characteristics of movement components that have been done in the past, so learning a new skill is abandoning an old habit and building a new one rather than learning a completely new motor skill. The associative stage becomes critical, connecting empirical findings with the relearning of a motor skill. Since an old habit has a built-in association with specific stimulus (*e.g.*, seeing a door, you prepare to pull a door), a new association must be made to progress into the later stage. This notion directly connects with the S-R compatibility as Fitts and Seeger (1953) found that a new association can be learned as subjects in their study improved both high and low compatibility S-R tasks. Fitts and Posner built this conceptual framework upon evidence from the information processing research. Therefore, the two most important implications from Fitts and Posner's learning stage model may be (1) cognitive process shifts as individuals learn motor skills and (2) learning is associated with reducing the amount of conscious processing, which allows individuals to respond faster and with less attention paid to the task.

Ten years later, Schneider and Shiffrin (1977) summarized empirical work of the information processing paradigm and proposed a dual-processing model rather than the three stages of motor learning. The first one is a "controlled process," which is activated under the performer's conscious attention. It is also characterized as a limited capacity. On the other hand, an "automatic process" is without capacity, and thus requires no attention, which is activated automatically in the absence of the performer's control. This automatic activation can be established by the strengthened association between S-R due to experience or practice. One distinction between Fitts and Posner's model and this model is that automatic process is a learned association. Consequently, automatic process can be gained within a few trials, depending on the feature of the stimuli (*e.g.*, finding a letter from a set of numbers). Contrary, Fitts and Posner's learning stage model dictates effortless task execution from repeated practice. Regardless of the subtle differences, there are great overlaps and common thoughts between Fitts and Posner's model and Schneider and Shiffrin's dual process model (Figure 2.4).

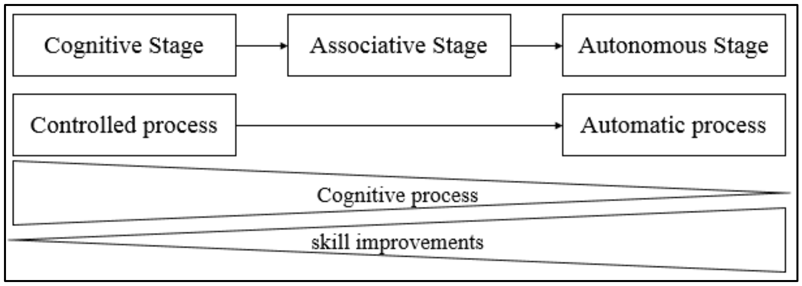


Figure 2.4. Conceptual Learning Model. Models are adapted from Fitts and Posner (1967) (top row) and Schneider and Shiffrin (1977) (middle row) and the Relationship Between Skill Improvements and Cognitive Process (bottom).

Speed Aiming Task and Motor Control

In this section, the theoretical model and literature review specific to an aiming skill will be introduced. Theories in the previous sections have received tremendous influence of research findings by studies in this paradigm. This paradigm is often referred to as Fitts Law, aiming task, goal-directed task, or speed-accuracy tradeoff paradigm and is largely known by Paul Fitts. Fitts (1954) conducted a reciprocal tapping task. In this task, participants are asked to tap on two targets with a stylus back and forth for a reciprocal tapping or move a stylus from a homing position to a target as fast and accurately as possible. Fitts measured movement time (MT) as a dependent variable by asking subjects to move as fast as possible while emphasizing on accuracy within a limited time (*e.g.*, 10 seconds). Fitts manipulated the distance (A as Amplitude) between targets and width (W, size of the target) and showed that as A increases and W decreases, MT increases (Figure 2.5).

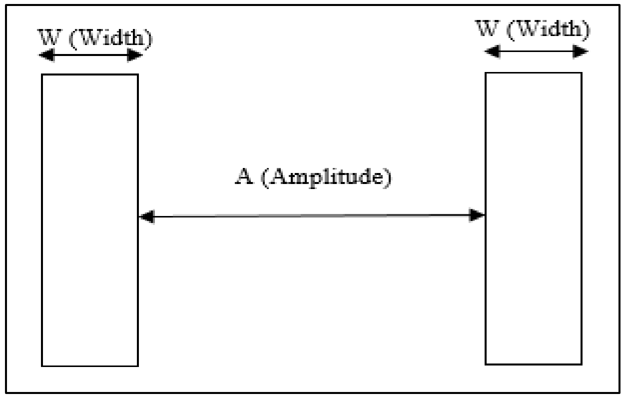


Figure 2.5. Traditional Experimental Design of Fitts' Law Task.

This study examined a fixed capacity of human information processing. Results showed the difficulty of the task can be expressed as Index of Difficulty (ID):

ID (Index of Difficulty) = $-\log_2 * W/2A$ or $\log_2 * 2A/W$

and index of performance (IP) is expressed as:

$IP = t * \log_{2*} 2A/W$

where t is the time it takes for each movement, representing information required to produce a movement in bits/second. From the finding that IP was relatively constant throughout different amplitudes of movements (i.e., different ID's) except for low ID's, he supported a relatively fixed human information processing capacity. Later, this study was supported in a discrete motor skill (Fitts & Peterson, 1964), and suggested that MT is predicted by:

MT = a + b ID

where a and b are empirical constants. The logarithm of base 2 function is based on the information processing theory that the transmission of information is expressed in bits as a certainty decreased by a half (Attneave, 1959). Lower ID indicates the information required to transmit is lower. As a result, it increases Gaussian noise (Fitts, 1954). The following section will discuss how a goal-directed aiming task is controlled in terms of MT and accuracy and variability of performance.

Theoretical Models for Movement Coordination

Although this paradigm is widely known by Fitts, the pioneers of this paradigm is Woodworth (1899), who first showed the accuracy and speed tradeoff relationship in an aiming task and proposed the motor control model for voluntary movements. In his series of studies, he asked participants to draw lines between targets reciprocally back and forth at different assigned speeds controlled by metronome beeps. This task was conducted with the right and left hand as well as with eyes open and closed conditions. The results showed there was a proportional increment of errors as the movement speed increased (errors above 2SD points were eliminated from the analysis) when visual information is available. This study showed a "tradeoff" between speed and accuracy of movements and the importance of visual information for movement corrections. Other important findings from this study were that (1) the error rate was not different in the two slowest movements (i.e., 20 and 40ms) and after a certain threshold (i.e., 140ms and faster); (2) even with a non-dominant hand, error was minimal if the movement was slow; (3) speed-accuracy tradeoff was not evident for the eyes-closed condition, but the difference between eye conditions diminished at a rapid movement speed (after 450ms). From these findings, Woodworth proposed the "Two-Component Model," which became a basis for the later models. The Two-Component Model proposes that the initial movement control (existence of movements from the start position to the target regardless of handedness or visual information) is an open loop and its goal is to bring the limb to the vicinity of the target (i.e., impulse phase); then, the limb positions are corrected prior to the hit on the target using feedback, and thus this is a closed-loop system (i.e., current control phase), where accuracy is dependent upon the time that participants have for movement corrections until the stylus reaches the target. Woodworth further proposed that the speed of visual feedback is approximately 450ms since no error correction was able to be made when the movement time is faster than 450ms regardless of visual information.

One of the greatest contributions of Woodworth (1899) is known to have found the visual process limit (Elliott, Helsen, & Chua, 2001) but at the same time, it was the biggest error. That is, his finding of 450ms included not only the time from the movement initiation to the target, but also the time to return to the original position (because it was a reciprocal tapping task). Thus, the time it takes until visual feedback begins to serve for movement corrections should be 450/2 = 225ms. Researchers resolved this issue (*e.g.*, Keele & Posner, 1968; Zelaznik, Hawkins, & Kisselburgh, 1983) and the visual feedback contribution in motor control is as fast as 100ms. These studies also found that visual information may serve as a feedforward system but plays a critical role in online control for accuracy (Elliot et al., 2001), and thus Woodworth's Two-Component Model is still informative in understanding motor control in voluntary aiming tasks.

Following the theoretical flaw of the visual information, Woodworth's Two-Component model was modified by Keele (1968) and Crossman and Goodeve (1983) and called the "iterative model." Keele (1968) explained the motor control in an aiming task from the motor program perspective. Keele proposed that the initial movement is executed by a motor program and if the time permits to process feedback (*e.g.*, visual and kinesthetic), another motor program is chosen for the movement correction (Elliott & Khan, 2010) and the error of the sub-movements are proportional to the remaining distance (Elliot et al., 2001). Thus, this model proposes the final accuracy is dependent upon the number of corrections. Later, more refined kinematic measurement techniques developed with the development of technology and revealed that Keele's proposition was not true. For example, Langolf, Chaffin, and Foulke (1976) revealed that the initial velocity was related to accuracy demands by calculating the "break-time," which represents the time that the second corrective movement occurs. Keele and Posner (1968) proposed this time would be about 200ms since the visual feedback took about 190-260ms in their study. However, Langolf et al. (1976) found that this was not constant. Instead, when the initial movement was faster (later break time), accuracy suffered, indicating the speed and accuracy tradeoff has something to do with the initial ballistic movement speed. Further, Langolf et al. (1976) found that the iterative model did not match with kinematic analysis of Fitts' Law task in the trajectory of a pin in a pegboard task. That study showed only one corrective movement was made following the initial impulse (Langolf, Chaffin, & Foulke, 1976). Consequently, this model was abandoned, and the single-correction model was proposed (Beggs & Howarth, 1972). Regardless of the differences in the models, all models agree with the importance of visual feedback for movement corrections, and the researchers emphasized on when this visual correction happens (*e.g.*, Beggs & Howarth, 1972; Keele & Posner, 1968).

Schmidt, Zelaznik, Hawkins, Frank, and Quinn (1979) proposed a different view regarding the motor control of an aiming skill that is largely influenced by the evidence of motor program. This model is known as the “impulse variability model,” proposing that accuracy is dependent upon variability of muscular forces that is used to propel the limb to the target since variability proportionally increases with force output. Therefore, error increases with an increase of absolute force required in the movement. Schmidt et al. (1979) provided strong evidence of this model. However, this model fit only for a rapid movement. When a movement was rapid, variability increased as the amplitude increased; however, movement correction is possible for a slower movement that takes longer than 200ms, so this model did not explain motor control of a goal-directed aiming task (Elliot & Khan, 2010).

Woodworth (1899), Keele and Posner (1968), Beggs and Howarth (1972) provided models regarding visual feedback and movement correction. Schmidt et al. (1979) provided evidence of the relationship between force output and error. However, none of the models perfectly explain the motor control. Thus, there was a need for modifications for the mechanism of goal-directed aiming tasks. Meyer, Abrams, Kornblum, Wright, and Smith (1988) integrated these models and proposed the “optimized submovement model.” According to this model, this Meyer et al. (1988) proposes that the noise of the movement is expected when the initial movement is made, and variability increases with speed or force associated with accelerating or decelerating the limbs. If the MT is similar across trials, the performance error is normally distributed around the center of the target and the tails of the distribution spread as force or speed of the movement increases. If the initial movement falls in the tail of this distribution, a correction is required for the subsequent submovements. This model accounts for both impulse variability and iterative models to explain how movement is corrected using visual and proprioceptive feedback while dealing with inherent noise.

Although the optimized submovement model is attractive, one of the biggest limitations of the model is that normal distribution around the center of the target does not occur when kinematics of the stylus is measured. That is, performers tend to undershoot but rarely overshoot the target (Elliot, Carson, Goodman, & Chua, 1991). Elliot et al. (2001) described this is because overshooting is costly from an energy consumption perspective. More recently, the optimized submovement model accounting for the energy expenditure is considered to be the most robust explanation for motor control of a goal-directed aiming task (Elliot, Hansen, Mendoza, & Trembley, 2004).

Open/Closed Systems and Motor Program Theories

The information processing theory explains the mechanism of the executive center. While this theory explains how we use perceived information to produce an output, one of the biggest limitations is that it does not explain the sensory contribution of motor control for future performance. There are two proposed systems explaining the mechanism of motor control: Closed and Open Loop systems. The first closed loop theory of motor behavior was proposed by Adams (1971,1987). A closed loop theory is the use of sensory feedback as a reference for the correction of movement execution for the next movement. Adams believed that sensory information imprints representation in memory and accumulates as practice, serving as a reference, which he called perceptual trace. With practice, “correct” perceptual trace accumulates more against incorrect outcomes (and thus incorrect perceptual trace), and thus learning occurs (Figure 2.6).

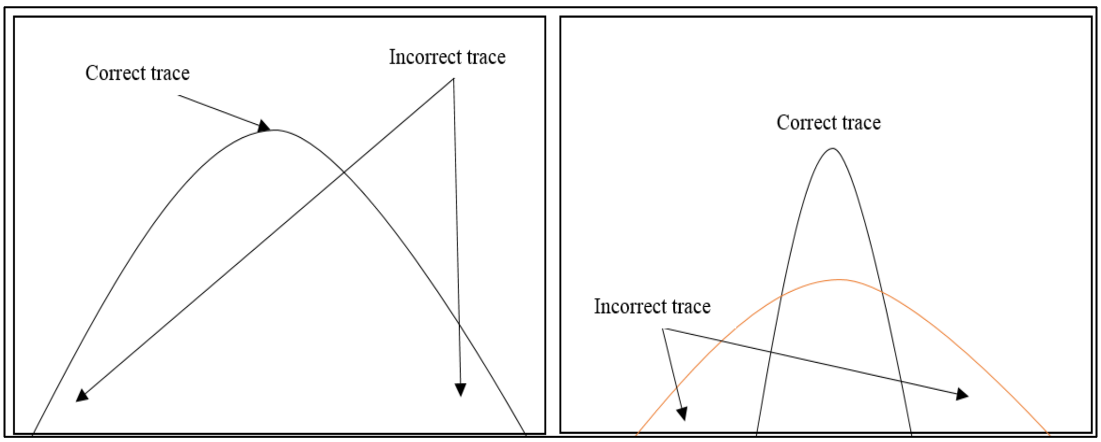


Figure 2.6. Accumulation of Perceptual Trace. The y axis represents the strength of the trace. Thus, as correct trace accumulates around the center with practice, less frequent incorrect traces lose its strength. Adapted from Schmidt and Lee (2005) *Motor control and learning: A behavioral emphasis* (4th ed.). Champaign, IL, US: Human Kinetics.

Here, the cognition evaluates performance outcome and perceptual trace. If the outcome—knowledge of results—and the sensory feedback are mismatched (i.e., incorrect movement), then memory trace, which is essentially the same concept of motor program, is modified, and memory trace initiates the next movement. However, this theory was rejected later because of evidence of practice variability (Shea & Kohl, 1991). That is, research in practice variability showed increasing variability increases performance errors and performance during practice is poor, but performance is superior in the retention test to practice in a more static practice environment. This cannot be explained by the closed loop theory since increased variability should result in a greater number of incorrect perceptual traces and should lead to a decline in a learning effect (Schmidt & Lee, 2005). However, Adams' theory stimulated numerous research and provided the importance of sensory feedback and motor learning. More contemporary thoughts of motor control and learning is a hybrid model in that a closed loop system (sensory feedback for movement correction) is embedded into an open loop system (Schmidt & Lee, 2005).

The open loop is an older theory proposed by James (1890) as Response Chaining Hypothesis. This hypothesis proposes that skilled movements seem to occur more unconsciously and require a sequence of muscle contractions at the correct timing. Thus, only the first generation of muscle contraction requires conscious process, and the sensory response from the first muscle contraction "triggers" a second contraction as if it were a chain reaction. It is an open loop because the subsequent movements are simply triggered by learned association between the preceded feedback and the next act in the sequence occurs as if a reward develops association with a specific response, reinforcing behavior. A study by Sherrington (1906) had been used for the support of the response-chaining hypothesis by observing how a monkey with his deafferented arm did not use his arm at all. However, Lashley (1917) found that a patient who lost afferent nerves from an accident was able to produce movements with less accuracy, indicating that sensory feedback does not trigger successive movements. Therefore, sensory feedback has something to do with accuracy of movements rather than causing movements (Schmidt & Lee, 2005).

Henry and Harrions (1961) empirically provided evidence that movement can occur prior to the arrival of sensory feedback. In this study, subjects were asked to do a simple RT task that requires them to move their arm forward and upward as soon as they see a “go” signal. In some trials, however, a “stop” signal was presented somewhere between a go signal and the completion of the task to cease the movement. First, subjects’ average RT was 214 ms and MT (movement time) was 199ms. Stop signals were presented at 110, 190, 270, and 350 ms following the go signal. An interesting finding was that subjects moved the limb even though the stop signal was presented at 190m, which was prior to the movement initiation. Moreover, Wadman, Denier, van der Gon, Geuze, and Mol (1979) showed that a rapid elbow extension exhibited a consistent temporal pattern of neuromuscular activation using electromyography (EMG) between agonist (biceps) and antagonist (triceps) muscles. Further, the study revealed that this specific pattern of activation was consistent when the subjects’ movements were unknowingly blocked, indicating this pattern of movements were “preset.” This “set” of commands that are seemingly determined prior to an actual movement has been considered as evidence of motor programs. Keele (1968) defined a motor program as, “a set of muscle commands that are structured before a movement sequence begins, and that allows the entire sequence to be carried out influentially by peripheral feedback” (pp.387).

Although the motor program theory may have solved the questions regarding how our movements are coordinated, there were two theoretical issues: the storage and novelty issues (Schmidt & Lee, 2005). If we possess motor programs for all necessary movements in our daily life and sporting activities, we must have an infinite number of programs. For example, throwing a ball overhand and quarter-hand require slightly different muscles and shoulder angle, so this requires two separate motor programs. Considering all potential combinations of throws, a motor program for throwing may require thousands of motor programs. The other issue is novelty. For instance, even adults often perform an unfamiliar movement, but they can roughly execute the action, although it may not be proficient. If the motor program commands are specific and the task is novel, they should not possess the motor program to execute the task. Therefore, modifications of the motor program theory were necessary. The modified and one of the most predominant theories in motor learning is the generalized motor program (GMP) theory. In contrast to the restricted definition of a motor program, a generalized program specifies a class of action (i.e., a pattern of movement) (Magill, 2007). Instead of a specific set of motor programs, GMP specifies a movement pattern of, for example, "handwriting." In this case, there are fixed patterns whether you write your signature bigger or smaller, or faster or slower. This fixed pattern is called invariant features; on the other hand, the duration of force applied, the size of the letters, or speed of movements are variables that are added to or modified based on the situation at the moment, and these are called parameters (Magill, 2007). In this way, instead of having infinite variations of handwriting, it requires only one GMP. This theory not only solves the storage problem but also solves how we can produce a movement in a novel situation. Schmidt (1975) proposed his version of GMP by modifying Adams' closed loop theory (1971). In his theory called schema theory (Schmidt, 1975), he proposed two sets of memory, recall memory and recognition memory. Recall memory is essentially a storage of GMP and parameters, while recognition memory serves as evaluation of response sensory information. Although it is important to note that this logic works well only for a discrete motor skill, Schmidt's GMP explains how we learn motor skills and has become one of the predominant theories by combining the characteristics of open and closed loop systems with a concept of memory representation.

In this section, a brief overview of historical progression of motor control and learning theories will be presented. Historically, the central interest of research was cognition based on the information processing theory. Researchers have also sought motor learning and control from the perspective of the integration of the executive system and peripheral systems, as William James proposed an open-loop system (1890) and Sherrington (1907) provided physiological evidence that is critical in human movement control. The development of theories began with new findings as Lashley (1917) found a motor command without sensory information in a patient who lost the sensory pathways or rejecting "old" thoughts as Adams departed from an open-loop system of animal learning (*e.g.*, Thorndike) towards Adams' closed loop theory about human motor learning (Adams, 1971, 1987). Theoretical limitations also served as an opportunity to develop theories as the memory drum theory by Henry and Rogers (1960) was rejected but their concept about motor memory is still valid, which contributed to the development of motor program theories with Lashley and others' work. The limitation of motor program theories and Adams' theory were integrated into the GMP theory and schema theory by Schmidt (1975). Theories of motor learning have grown by modifying limitations of previously proposed theories around the concept of the executive-center oriented behavioral change. In the next section, a significant departure from this concept is introduced.

Dynamic Systems Theory

A different view of motor control and learning has emerged outside the psychological theories called the dynamic systems theory. This section begins with a conceptual framework of the dynamic systems theory, and then measurement methods and findings will be discussed.

This theory originates from phenomena in physics, biology, meteorology, engineering, chemistry, and other disciplines (Davids, Glazier, Araujo, & Barlett, 2003). Kelso (1995) described that phenomena seen outside motor behavior can also be consistent in humans. One of the central tenets of the dynamic systems theory is the departure from the reductionism of the information processing theory in that understanding parts (inputs) will lead to the understanding of the whole. In the physical system, this is not always the case. Kelso used an example of boiling water in a pan. Water molecules at a room temperature move randomly, seemingly move independently, and do not show any complex behavior. The degree of freedom (DOF) of water molecules is infinite. However, once it is heated from the bottom of the pan, cooler water molecules around the surface begin to sink toward the bottom and warmer molecules move upwards, creating an organized circular motion known as convection. Now, the DOF of this new behavior is condensed and the molecules move as a unit. There is no way to predict this spontaneous change of behavior by observing a single water molecule. Thus, small, simple factors can produce a very different and complex behavior, and the output is not the sum of inputs. Additionally, there is no “executive center” for this behavior. Rather, behavior is “shaped” by heating water in the pan. Newell (1986) described that behavior is shaped based on the individual, task, and environmental constraints (Figure 2.7).

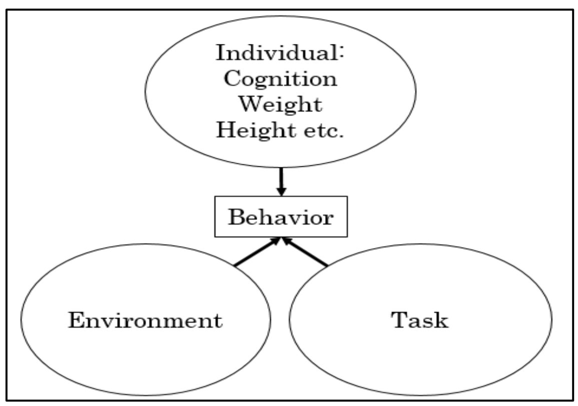


Figure 2.7. Dynamic Systems Model of Behavior Based on Constraints. Figure is adapted from Newell (1986). Constraints on the development of coordination. In M. G. Wade & H. T. A. Whiting (Eds.). Motor development in children: Aspects of coordination and control (pp.341-361). Amsterdam: Nijhoff.

As shown in this boiling water example, the central theme to the dynamic systems theory is “self-organization” such that behavior is organized by itself based on constraints placed upon it, which is called control parameter (Kelso, 1995). Each system has a stable state, called attractor state, with a specific coordination, called coordinative structure. When this attractor state is disturbed by various constraints, it becomes unstable; when this disturbance reaches a certain threshold, a spontaneous change in behavior (*i.e.*, phase transition) occurs and a new complex coordinative structure is shaped, and the system goes back to a stable state (Haken, Kelso, & Bunz, 1985). This change has been shown in humans (Kelso & Holt,1980; Kelso, 1984). Therefore, observing the changes in variability (*i.e.*, stability and instability) and understanding control parameters may allow us to quantify motor control and specify variables that affect behavior or behavioral change. This may help answer questions related to motor behavior transitions such as why infants change their behavior from crawling to walking (Thelen & Ulrich, 1991).

Movement Variability and Motor Learning

Bernstein stipulated how we control numerous biomechanical DOF of movements (Bernstein, 1967) to further the field in movement variability. When learning how to throw a ball, there are infinite biomechanical DOF (*e.g.*, fingers, hands, shoulder, trunk, and leg) to control. His supposition was derived from the observation of a craft man making a chisel with a hammer. The observation was consistent performance variability but different movement coordination with each hit. This implies movement variability may show characteristics that are meaningful to understand motor learning. He proposed that motor learning takes a hierarchical progression from "freezing" of the DOF into a manageable one, toward releasing the DOF to incorporate available DOF, and then toward exploitation of the DOF to produce a coordinated structure of movements. That is, motor learning is considered as mastering the redundant DOF into a controllable system (Newell, 1991). This notion was empirically supported that learning in the initial stage resulted in smaller variability of joint segment movements when learning a ski-slalom, and the skill improvements (*i.e.*, reducing performance variability) coincide with increased DOF (*i.e.*, increase in the joint variability) (Verejiken, van Emmerik, Whiting, & Newell,1992). In the following sections, how this fundamental thought took different paths and theories will be discussed.

Variability as Nonlinear Dynamics

Another aspect of the dynamic systems theory is derived from a theory called the chaos theory. Traditionally, motor learning has been inferred from performance average and its standard deviation (SD). As shown earlier, human systems are imperfect. This fact has placed the importance of reporting the mean of performance in science. Due to this variable nature of performance, variability has been considered as task-irrelevant errors or random errors known as “noise” (Slifkin & Newell, 1998). Specifically, any of the information processing theories considered that noise naturally exists in the information processing and is less meaningful because it is considered as Gaussian noise (*i.e.*, fluctuations that are independent from sample to sample) (*e.g.*, Fitts, 1954; Schmidt et al.,1979). For this logic, performance outcomes are collapsed into a mean of many trials (*e.g.*, a mean and SD of 10 trials in each block). However, the dynamic systems theory instead considers that trial-to-trial variability may provide meaningful information that is distinguishable from noise (Stegirou & Decker, 2011). For example, Slifkin and Newell (1998) presented how seemingly different signals that actually have the same mean and SD can be quantified by applying different metrics (*i.e.*, autocorrelation in this case) (Figure 2.8).

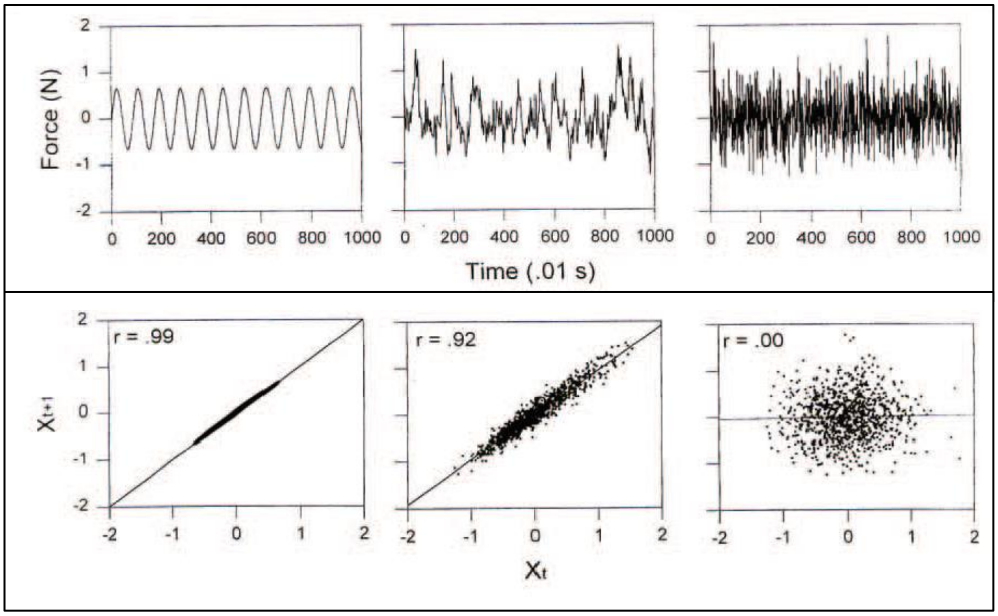


Figure 2.8. Three Different Time-Series Signals Possessing the Same Mean and SD. Top row shows signals. The bottom row shows autocorrelation. The differences are captured in autocorrelation from perfectly regular (left) seemingly irregular but possesses a strong relation in time-to-time variability (middle) and completely random (right). Figures are retrieved from Slifkin and Newell (1998).

In the middle figure in Figure 2.8, r = .92 indicates variability of one-time point is strongly correlated with variability in next time point. That is, it appears to be a random structure, but the system actually has "memory" in that fluctuations are related, showing a "hidden structure" that cannot be captured by the traditional methods (Stegirou & Decker, 2011). Newell and Vaillancourt (2001) considered this approach can bring us to a new trajectory to move the science forward by regarding that Bernstein's learning model does not move the science beyond his conceptual framework and is situation specific since the movement variability increases or decreases depending on the task (*e.g.*, Broderick & Newell, 1999; Zaal, Diagle, Gottlieb, & Thelen, 1999).

Autocorrelation is not the only measure of unraveling a hidden structure. Another method to examine variability in time series is called entropy. This method measures predictability of a system. One of the entropy measures, approximate entropy provides a single value that predicts a system's structure that is either completely predictable (lower value) towards the other extreme end, completely random or disordered (higher value) (Slifkin & Newell, 1998). Earlier, Schmidt et al. (1979) predicted in the impulse variability model of a goal-directed aiming task that noise increases as the required force output increases. This indicates the information transmission increases with the amplitude increases. Slifkin and Newell (1999) examined this in an isometric force production at varying force output levels (5 – 95% of maximum voluntary contraction, MVC). The results showed that the variability of force output around the mean increased as required force production increased, which was predicted by Schmidt et al. (1979). However, Slifkin and Newell also measured the signal-to-noise ratio (M/ SD) and showed that the optimal signal-to-noise ratio reached around 35% of MVC, indicating the optimal information transmission occurred around this point, which contradicts with the prediction by Schmidt et al. (1979). This result coincided with the approximate entropy, showing that the greater entropy was observed around 35% MVC (approximately .6) and low entropy (approximately .5) around 5% and 95% of MVC. One of the greatest advantages of this metric is that it provides quantifiable values.

Interestingly, this is not the only use of variability. For example, a random appearance of coastline or cloud shows a geometrically similar pattern of its subscales when it is magnified (Lipsitz, 2002; Lipsitz & Goldberger, 1992). This structure also has a similar pattern when it is magnified and analyzed its sub-scaled structure. This self-similarity is called “fractals.” When examining, for example, gait variability or other motor skills, research has shown a fractal pattern in a time or frequency domain data. How much the data is “random” or “consistent” is captured by measuring “complexity” as shown in entropy. The extreme randomness or predictability has been shown to be related to pathology (Brach, Berlin, VanSwearingen, Newman, & Studenski, 2005; Goldberger, Peng, & Lipsitz, 2002) or ageing (Vaillancourt & Newell, 2003). Studies have revealed too much or little variability is not ideal (Vaillancourt & Newell, 2001) and somewhere in the middle called “pink noise” or “1/f” signal has been indicated to be better (in a relative term) (Dinzi et al., 2011).

Research introduced above has shown many different theories from different perspectives in motor control and learning. Researchers in motor learning are not only interested in how humans learn motor skills, but the effectiveness of different instructional strategies such as verbal instructions, augmented feedback, demonstration, and practice schedule (Magill, 2007). One of the extensively studied areas in examining instructional strategies in motor performance and learning of motor skills is attentional focus. In the following sections, findings, and theories of attentional focus on motor skill acquisition will be discussed.

Attentional Focus

Attentional focus in psychology is analogous to selective attention. In motor learning, it is defined as consciously paying attention or thinking about a certain cue (Magill, 2007). Historically, selective attention has been studied in a task that has minimum motor components (*e.g.*, pressing a button) since psychologists' primary interest is to understand the mind through response (action), not the opposite. Considering the findings that the same principles in research with a fine motor skill do not apply to a more complex skill (Wulf & Shea, 1999), studies of attention in psychology may not apply to the majority of studies conducted in Kinesiology, and the history of attentional focus in a more complex skill is much younger than the history of attention itself. As a result, there are still equivocal conclusions and hypotheses explaining the mechanism of attentional focus.

History of attentional focus can be traced back to the 1800's as William James (1890) described "keep your eye at the place aimed at, and your hand will fetch the target; think of your hand, and you will likely miss your aim" (p.520). In a more recent empirical work, Henry (1953) showed directing subjects' attention to the position of the pad resulted in better performance (*i.e.*, maintaining the position of the pad that randomly moved) compared to directing subjects' attention to the hand (*i.e.*, attention to kinesthetic sensations). Later Henry (1960) defined "motor sets" as paying attention to the movement of the body and "sensory sets" as focusing on the stimulus that is related to corresponding response and discussed motor sets would disrupt performance execution. However, there was little follow up research regarding attentional focus effects on motor performance (Christina, 1973).

Extensive work in attentional focus on motor control and motor learning regained its attention in the 1990's. Researchers from sport psychology, motor learning, and psychology have differently defined attentional focus. For attentional focus research in motor performance, there are several important characteristics. First, most of the defined attentional focus strategies are dichotomous, and thus comparison is usually not in relation to a “control” condition. This is because (1) we cannot experimentally “control” one’s mind and (2) a control condition would, by design, contain less information than the treatment (attentional focus) groups. Secondly, the results are largely dependent upon the operational definition. Although the present review will focus on the two most related categories, attentional focus strategies are generally categorized as a comparison between task-relevant and task-irrelevant cues or task-relevant and other task-relevant cues (Figure 2.9). Lastly, the attentional focus strategies in the motor learning is specific to motor control attention rather than attention as arousal, which is one of the limitations of this paradigm for the lack of consideration in other components that may play an important role in attentional control.

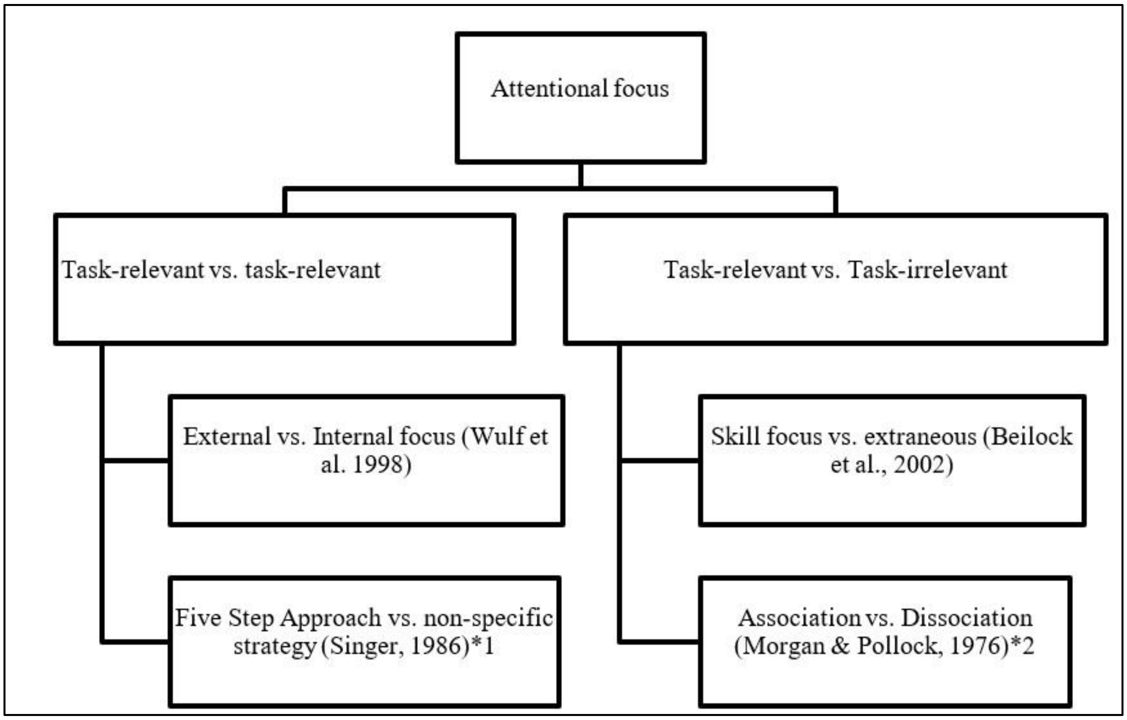


Figure 2.9. Attentional Focus Strategies in Motor Learning. *1 Five Step Approach is not included in the review since this method is an integration of multiple topics including attentional focus in motor learning. *2 Associative and dissociative attention is not included in the review since this paradigm is limited to endurance activities.

Attentional Focus as Task-Relevant vs. Task-Irrelevant

In the context of attentional focus, one type of attentional focus strategy is comparing attention directed to a task-relevant or task-irrelevant cue. One may wonder, "how can directing attention to a task-irrelevant cue be a good candidate relative to a task-relevant cue?" The reason lies in the relationship between attentional focus and "knowledge system." According to Beilock and Carr (2001), knowledge about skill performance is accessed through Generic knowledge ("schema-like or prescriptive information about how a skill is typically done, (pp.702)") and episodic knowledge ("a specific memory—an autobiographical record of a particular performance (pp.702)").

Experts accumulate information about the skill (Logan, 1985), so generic knowledge should increase with expertise. Contrary to this, episodic knowledge decreases with practice (Beilock, Wierenga, & Carr, 2002). This is believed to happen because performing a well-learned skill is automated (Fitts & Posner, 1967; Schneider & Shiffrin, 1977), and thus requires no online attention (accessing working memory). Researchers in this paradigm have found that where you pay attention to during practice (*i.e.*, attentional focus) influences the knowledge system, and this, in turn, affects performance in the retention contexts, especially under pressure. For example, teaching the regularity of movements (*i.e.*, conscious process of learning the rules governing a skill performance or "explicit learning") did not lead to greater learning compared to simply telling performers to do their best (*i.e.*, unconscious process of discovering the rules governing the skill, or "implicit learning") (Green & Flowers, 1991; Reber, 1967, 1989; Robertson, 2007; Wulf & Weigelt, 1997). The benefit of implicit learning or decrement of explicit learning becomes even clearer under pressure (Beilock, Carr, McMahone, & Starkes, 2002; Lewis & Linder, 1997; Masters, 1992). As a result, researchers have sought an effective attentional focus strategy during practice that does not lead to performance decrement under pressure (Beilock & Gray, 2007 for review). Beilock et al. (2002) adopted a dual-task procedure (extraneous focus) to prevent explicit monitoring of a task, whereas explicit learning was encouraged by directing attention to skill. The results showed that skill focused attention is detrimental in experts, but skill focused was beneficial for novices. This was replicated later that the benefits of the extraneous or skill focused attention is skill-level dependent (Beilock, Bertenthal, McCoy, & Carr, 2004; Beilock &

Gray, 2012). These studies have shown that attentional focus during practice influences how performers respond to a high-pressure situation.

Attentional Focus as Task-Relevant vs. Task-Relevant

Unlike skill focused and extraneous attention, the next category of attentional focus compares a task-relevant cue with a different task-relevant cue. One of the potential limitations of the skill focused attention and extraneous attention paradigm (Beilock et al., 2002) is that it is unclear as to what part of the skill performers were paying attention to. That is, it is possible that participants were thinking about body movements in general, specific parts of body movements, movements of an object that the performer is manipulating (*e.g.*, club), or sensations that are related to skill execution (Wulf, 2013).

Wulf, Hob, and Prinz (1998) defined two foci: External Focus (EXF) and Internal Focus (INF). EXF is defined as directing performers' attention to the effects of the movements on the environment, where INF is defined as directing performers' attention to body (part) movements. In this original study (Exp.1), participants practiced a ski-slalom simulation task (Figure 2.10) to exert as large of an amplitude and frequency to the sides of the platform as possible. Participants in the EXF group practiced the task and were told to focus on the movement of the wheels (that was beneath the platform), while the INF group was told to focus on the movement of their feet. Participants in the control (CON) group received only the goal of the task. Results of the study revealed that the EXF produced larger amplitudes relative to the INF during practice (Day 2) and relative to both INF and CON (no difference between INF and CON) in the retention test (Day 3).

Since this original study, the benefits of an EXF instruction has been examined in various motor skills Wulf, 2013).

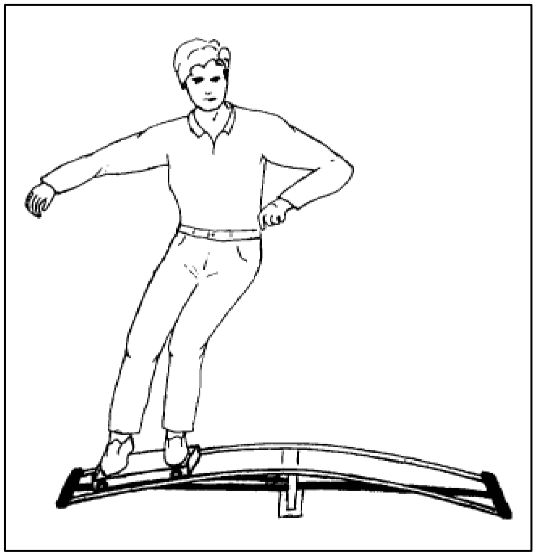


Figure 2.10. Ski-Slalom Simulation Task. Participants stand on a platform that was guided by wheels on the convex rails. Platform is attached with resistance bands so that it moves back to the apex of the rails if no force is applied to any directions. Adapted from Wulf, G., Höß,M., & Prinz, W. (1998). Instructions for motor learning: Differential effects of internal versus external focus of attention. *Journal of Motor Behavior*, *30*(2), 169–179.

There are some specific characteristics for the operational definitions of EXF and INF. First, EXF and INF have specific contexts. INF is kinematic movements rather than the feeling of movements (*i.e.*, kinesthetic) or thoughts (*e.g.*, associative and dissociative attention by Morgan & Pollock, 1977). Secondly, EXF is specifically "the effects" of the movement, not something outside. In contrast, other literature defined "external" as generally distracting from the task-relevant cues (*e.g.*, extraneous focus by Beilock & Carr, 2001; dissociative attention by Morgan & Pollock, 1977). A study, for example, examined this distinction in tennis service returns (Wulf, McNevin, Fuchs, Ritter, &

Toole, 2000). One group of participants was told to direct their attention to the ball that is coming toward them from the machine (*i.e.*, external as “outside”) and the other group was told to direct their attention to the desired trajectory of the ball that participants would be hitting (*i.e.*, external as “effects of movements”). The results showed that directing attention to *the effect of the movement* outperformed the group of participants who directed their attention to simply outside the body. This finding was later replicated, indicating the importance of directing attention to the effects rather than something outside the body (Russell, Porter, Campbell, 2014; Wulf, McNevin, 2003). Unfortunately, a number of literature compares the effects of attentional focus with other attention foci that do not fit these characteristics (Wulf, 2013).

Amongst the research that adopted the above-mentioned specific characteristics of EXF and INF, the benefits of EXF have consistently been shown in various motor skills and populations. In the following section, attentional focus effects in this paradigm in various motor skills are described.

One of the early studies in motor skills that require accuracy was golf chipping toward the goal that was 15m away (Wulf, Lauterbach, & Toole, 1999). Participants in the INF group received multiple instructions regarding the golf swing (backswing, during the swing, and at the moment of hitting the ball), but their attention was directed toward their arm movements. On the other hand, participants in the EXF group received instructions but their attention was directed to the club motion. The results of accuracy (distance relative to the goal) revealed that the EXF was superior to the INF both in practice and in the retention test. The benefit of EXF in golf was replicated in chipping at farther distance (*e.g.*, 20m for Bell & Hardy, 2009; 25m for Wulf & Su, 2007), putting (Keanery, 2015) and iron and driver shots (Christina & Alpenphal, 2014). Marchant, Clough, and Crawshaw (2007) adopted the multiple instructions used by Wulf et al. (1999) in dart throwing and replicated the benefits of EXF. Lohse, Sherwood, and Healy (2010, 2014) modified attentional focus instructions by explicitly telling participants to, "visually focus on ...mentally focus on…" to distinguish visual and cognitive attention. Interestingly, the superior effect of EXF was still evident.

The benefits of EXF over INF have also been replicated in motor skills that require an explosive force output in a limited time. Porter, Ostrowski, Nolan, and Wu (2010b) examined standing long jump, and the EXF group adopted "focus on jumping as far past the starting line and the INF group adopted "focus on extending your knees as rapidly as possible." Results from this study showed that the EXF jumped farther immediately following receiving the instruction. These beneficial effects of EXF have been replicated in standing long jump (Becker & Smith, 2015; Ducharme, Wu, Lim, Porter, & Gerald, 2015; Makaruk, Porter, Czaplicki, Sadwski, & Sacewicz, 2012; Porter, Anton, Wikoff, & Ostrowski, 2013; Wu, Porter, & Brown, 2012), counter movement jump (Keller, Lauber,Gottschalk, & Taube, 2014; Makaruk et al., 2012), shot put (Makaruk, Porter, & Makaruk, 2013), discuss throw (Zarghami, Saemi, & Fathi, 2012), 10m sprinting (Winkelman, Clark, Ryan, 2017 Exp.1), sprint start (Ille, Selin, Do, & Thon, 2013), agility (Porter, Nolan, Ostrowski, & Wulf, 2010a), lower leg extension with loads (Halperin, Williams, Martin, & Chapman, 2015), and isokinetic elbow flexion (Marchant, Greig, & Scott, 2009).

While aforementioned studies were sport skills, the beneficial effect of EXF has also been reported in balance tasks, which may provide more insight to clinical populations. In the second experiment of Wulf et al. (1998), participants were asked to stand on an unstable platform each 90-second trial, and participants in the EXF group were told to focus on keeping the platform level with the ground while participants in the INF group were told to focus on keeping their feet level with the ground. The results, again, showed the balance performance was better in the EXF group relative to the INF group in root mean square error as a reference point (x, y) = (0,0) (*i.e.*, board parallel to the floor). The effect of attentional focus instructions in balance/postural control has been replicated in various studies (Landers, Wulf, Wallmann, & Gaudagnoli, 2005; McNevin, Wulf, & Shea, 2003; Wulf, Landers, Lewthwaite, & Tollner, 2009; Wulf, McNevin, & Shea, 2001a; Wulf, Shea, & Park, 2001b, Wulf, Tollner, & Shea, 2007).

EXF is not only effective on performance outcomes, but attentional focus has also been shown to influence movement mechanics. For example, Wulf, McConnel, Gartner, and Schwarz (2002, Exp.2) adopted EXF and INF augmented feedback to novices and skilled volleyball players and examined volleyball serve performance and its movement form. The results showed the quality of volleyball serve form scored by experienced coaches were better with EXF feedback than INF feedback. The effective EXF in movement quality has also been reported in soccer ball throwing (Wulf, Chiviacowsky, Schiller, & Avila, 2010), ballet sequence movements (Abdollahipour, Wulf, Psotta, & Nieto, 2015), and swing path of golf swings (Christina & Alpenfals, 2014).

Mechanism of Attention and Action

The origin of the EXF/INF paradigm stems from theories of perception and action. For example, Prinz (1992; 1997) proposed that action is best planned by thinking about an intended effect, using a common coding approach—the action effect hypothesis. According to Prinz, the history of action planning dates back to the1600's and the same concept lasted until the 19th century. This old view was that sensory codes and action codes were incommensurate in the process of perception-action coupling because one is to stimulate sensory organs and the other is to stimulate muscles. Consequently, this requires translation of the two different codes (language). However, a more recent thought is that the brain does not differentiate the body from the environment, so the only way the brain distinguishes an environment moving from the body moving is whether that motion is made by will or not. That is, when you see a bird flying outside the window (perception) and you try to move it; you certainly cannot move the bird or are not moving it, but you realize you can move and are moving your finger. That is, the only difference in the external event (bird moving or your body moving) is the latter is moved by your intention. Thus, there is no translation between percepts and actions. Elsner and Hommel (2001) supported a similar view—the ideomotor theory—using the results from the S-R paradigm studies, which is described above: Participants who learned a tone to produce a specific movement led to a faster RT but RT slowed for an unlearned tone, suggesting that planned action and perception (tone) needs to be associated and action plan is made based on the anticipated sensory response. This may be similar to Adams' closed loop theory (1971), which was described earlier. However, the difference is that

Adams (1971) explained the response effects (what you felt, how you felt) serve as a knowledge of result for motor evaluation; but the ideomotor theory dictates that the response effect is a part of motor generation (Koch, Keller, & Prinz, 2004). In this sense, the ideomotor theory is almost identical to the memory drum theory (Henry & Roger, 1960) that proposes that action (neuromotor memory) is better with "sensory set" (action focused on the stimulus to be responded) than "motor set" (action focused on the movements to be made), which Henry (1953) provided an empirical evidence of this notion.

The Mechanism of the EXF/INF

The effect of an EXF and INF on motor performance has been generally explained by the Constrained Action Hypothesis (CAH) (McNevin et al., 2003; Wulf et al., 2001a, 2001b), proposing that internal focus disrupts motor coordination while external focus promotes an automated processing. The latter part is largely derived from Gabriele Wulf's personal experience (Wulf et al., 1998) and the action effect hypothesis (Prinz, 1992; 1997). For the former part of the detrimental effect of an INF, the CAH has been supported generally by three lines of research: Neuromuscular coordination using electromyography (EMG), dual-task procedure, and movement adjustments in postural control as a mean power frequency (MPF).

Vance, Wulf, Tollner, McNevin, and Mercer (2004) showed that integrated EMG (iEMG) during elbow flexion at 50% of participants 1-repetition maximum (RM) was higher during the INF (focus on the biceps muscles) relative to the EXF (focus on the bar) condition. Vance et al. concluded that the results suggest either EXF promotes efficient neuromuscular coordination or INF promotes less efficient coordination. These findings have been replicated in maximum elbow flexions (Marchant et al., 2009), elbow flexions at different movement speeds (Greig & Marchant, 2014), and in leg extensions (Marchant & Greig, 2017) or ankle flexions (Lohse & Sherwood, 2012; Lohse, Sherwood, Healy, 2011). Further, Lohse and Sherwood (2012) and Lohse et al. (2011) showed INF increased co-contraction ratio between agonist and antagonist muscles, which increases stiffness at the joint. This inefficient neuromuscular coordination was also evident in sport skills that require accuracy (Lohse et al., 2010 in dart throwing; Zachry, Wulf, Mercer, & Bezodis, 2005 in basketball shooting). Zachry et al. (2005) concluded that INF adds "noise" to the motor system, which interferes with motor skill performance.

The support of the CAH has also been supported by a procedure which examines attentional capacity. Wulf et al. (2001) examined a probe reaction time (RT) task as a secondary task while participants performed a balance task on an unstable platform with either an EXF or INF. During the balance task, auditory stimuli were introduced. The EXF were told to focus on keeping the tapes (on the platform) at the same level and press the button in their hands as soon as they hear the tones. The INF group performed in the same manner but were told to focus on keeping their feet at the same level. The results showed the EXF group had a greater balance and faster RT relative to the INF group. Wulf et al. (2001) concluded that attention demands are reduced when individuals use an EXF. As introduced in the motor learning section, reduced attentional demands are characteristics of motor skill learning (Magill, 2007) since less attention is required when the task is well learned (Fitts & Posner, 1967). Thus, EXF may promote cognitive behavior that is represented in a well-learned skill. One concern regarding the experimental design was that it is possible that participants in Wulf et al. (2001) allocated their attention only when the auditory stimuli were presented during the dual-task procedure. However, the efficient attentional capacity of an EXF was recently replicated in a dual task that requires more continuous attention to the secondary task (*i.e.*, a letter fluency task) (Kal, van der Kamp, & Houdijk, 2013).

Wulf et al. (2001a; 2001b) used mean power frequency (MPF) to analyze the postural control behavior between different foci. This method Wulf et al. (2001a; 2001b) and McNevin et al. (2003) provided evidence of greater MPF when participants used an EXF instruction relative to an INF instruction during a balance task on a stabilometer. This suggests that EXF promoted subtler postural adjustments (*i.e.,* greater high frequency components), which may contribute to higher postural control ability.

Attentional Focus from the Dynamical Systems Perspective

The above-mentioned studies supported the constrained action hypothesis. However, the CAH does not explain how this neuromotor coordination changes occur. With this regard, the CAH has been criticized for the incomplete explanation of the mechanism (Lohse et al., 2014; Oudejans et al., 2007). More recently, some researchers have applied the dynamical system perspective to understand the mechanism of attentional focus effects on the motor behavior. One of the earliest researchers who adopted this method was Lohse et al. (2010) in this study, participants practicing a dart throw were examined using two-dimensional kinematics of shoulder and elbow angle variability in different phases of the throws (*e.g.*, retraction and extension of the arm). The results found that an EXF led to a greater elbow angle variability with more consistent performance relative to an INF, supporting Bernstein's concept (1967) regarding the freeing the degree of movements. The finding by Lohse et al. (2010) was replicated when examining the inter-segment relationship between shoulder joint variability and elbow joint variability correlation within the redundant subspace (Lohse et al., 2014). Fietzer, Winstein, and Kulig (2018) also found that an EXF led to a greater movement variability that led to performance stabilization, using an uncontrolled manifold method. Another major metric that has been adopted in the dynamical systems is sample entropy, which detects complexity of movements. Kal, van der Kamp, and Houdjik (2013) used this method to examine the regularity of movements in leg flexion and extension and found that an EXF led to a greater sample entropy, which is indicative of more complex movement regularity, relative to an INF. These studies have provided a new insight in the attentional focus paradigm in that an EXF may promote individuals to exploit available degrees of freedom, while an INF freezes the degree of movements, which may result in poorer performance.

However, more recent studies revealed that the interpretation may require further investigation. For example, Diekfuss, Rhea, Schmitz et al. (2018) did not find the EXF/INF difference in a sample entropy while both groups decreased sample entropy in the velocity of the board in a balance board task. Further, Vaz, Avelar, and Resende (2019) found no difference between an EXF and INF in multiscale entropy of trunk and platform data in a balance task. In contrast to Kal et al. (2013), Vaz et al. (2019) found a trend of lower entropy in the INF group. Vaz et al. (2019) concluded whether a high or lower entropy indicates more proficient performance is task specific. Consequently, more extensive studies are imperative to understand the relationship between entropy measures and attentional focus.Vidal, Wu, Nakajima, and Becker (2018) also examined the joint-joint coordination variability in a standing long jump performance. However, the study did not support the results by Lohse et al. (2014). Further, Yogev-Seligmann, Sprecher, and Kodesh (2017) did not find gait variability between EXF and INF instructions. Thus, the relationship of an EXF and INF in movement variability has still been unclear.

When studies examine motor coordination rather than movement variability, the findings are further equivocal. For example, Kal et al. (2013) examined jerks in the knee flexion/extension movements as an indicator of movement fluency, since greater jerk implies more changes in acceleration throughout the movements (*i.e.,* less smooth movements). The study found that an EXF had greater fluency of movements relative to an INF. However, this finding was the exact opposite in the same task in stroke patients (Kal, van der Kamp, Houdjik et al., 2015). Southard (2013) which showed the EXF benefits by increasing the time delay of the proximal-distal segment in a baseball pitching relative to an INF. Vidal et al. (2018) found that INF showed more knee phase predominantly during the downward phase of a standing long jump prior to takeoff, which was not evident in the EXF condition. However, the study did not find any differences between an EXF and INF in all other variables except for this one variable. Therefore, the knowledge about how attentional focus affects movement variability or motor coordination is immature.

Gaps in the Literature

Although the beneficial effect of EXF relative to INF in performance is generally robust, there are several concerns regarding the effect of attentional focus instructions:

(A) The Constrained Action Hypothesis (CAH) (McNevin et al., 2003; Wulf et al., 2001a, 2001b) explains that an EXF promotes an automated motor coordination and INF disrupts the motor system. However, the mechanism regarding how these changes of motor coordination occurs is still unclear. The lack of explanation may stem from how the CAH is proposed. The CAH proposes only the effect of attention. As a result, it may lack in the appreciation of the general motor learning theories. Some researchers recommended applying a broader theoretical framework (Lohse et al., 2014; Oudejans, et al., 2007). For example, Landers et al. (2005) showed that postural control with an EXF and INF instruction in older adults with Parkinson's disease did not differ when the task was easier (*i.e.*, simply standing quietly), but the EXF condition outperformed the INF condition when the task became more challenging (*i.e.*, eyes closed with platform moved in accordance with postural sway). This finding was consistent with Wulf et al. (2007) and more recently with Becker and Smith (2013). These studies suggest a potential moderation effect of attentional focus strategies. This potential moderation may be understood by applying the information theory. Using Fitts and Posner's learning model (1967), it allows us to hypothesize that performing easy tasks requires less cognitive process, and thus attentional focus effects may be less influential; on the other hand, performing difficult tasks requires a large online process, which may overwhelm the performer, and thus a provided instruction may be ignored. This is a testable framework by examining mental load and the memory of instructions.

(B) The moderation effect may not be solely due to the contexts of the practice environment. A recent theoretical model embraces psychological influences on motor performance and learning (Wulf & Lewthwaite, 2017). However, the effect of attentional focus instructions on the psychological aspects is still unclear. It is possible that performance is largely affected by perceived mental load or performance competence, which may potentially influence the relationship between an EXF and INF and mechanism of the attentional focus and the learning of motor skills.

(C) Another potential solution to develop the understanding of attentional focus effects may be to apply the dynamic systems theory to understand time series of variability. This approach may reveal "hidden structure" of performance that may not be evident from collapsed mean and SD of performance. As mentioned above, some researchers have adopted this approach (*e.g.*, Diekfuss et al., 2018; Kal et al., 2013; Lohse et al., 2014; Vaz et al., 2019; Vidal et al., 2018). However, the findings are still equivocal. One of the potential reasons for the inconsistency is that almost all research used different methodologies to investigate the effect of attentional focus from the dynamic systems theory except for Diekfuss et al. (2018) and Kal et al. (2013) (*i.e.*, sample entropy). Vaz et al. (2019) suggested that entropy metrics may be task specific. That is, the system requiring a constant time-series fluctuation (*e.g.*, postural control, maintaining blood pressure) has shown that a greater entropy indicates meaningfully complex structure, while the lower entropy is indicative of a "pink" noise system for the system requiring a cyclic attractor (*e.g.*, gait). For dynamic balance, it is neither perfectly fixed nor cyclic. However, it is logical to consider that predictability increases (more consistent performance) for a dynamic balance, which should be indicated by a lower entropy, while more rigid movements in a fixed attractor system have shown to be related to pathology. This logic follows well with empirical findings that an EXF increased a sample entropy for a postural control (Rhea, Diekfuss, Fairbrother, & Raisbeck, 2019), while practicing dynamic balance reduced entropy (Diekfuss et al., 2018). Therefore, metrics used for the dynamic systems theory may provide further insight of attentional focus effects on human motor behavior.

Previous Research

Raisbeck et al. (2020) examined the effect of attentional focus and task difficulty. Participants (*N* = 26) for this study sat in a chair in front of a table with two targets (5 x 5 cm) positioned on the table. Participants were asked to move a cube (5 x 5 x 5 cm) back and forth and tap the targets as accurately as possible at a designated speed (90BPM) with metronome beeps (Figure 2.11).

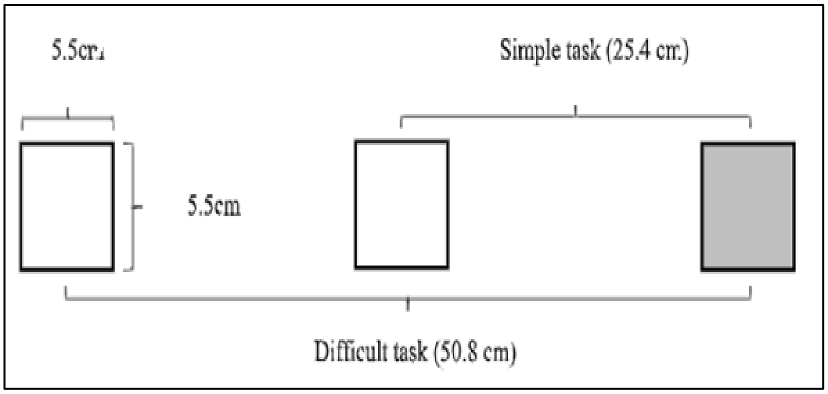


Figure 2.11. Task Difficulty Manipulation by Raisbeck et al. (2020). Participants moved the cube at 90BPM.

In one condition, participants moved a cube between the targets distanced at 25.4 cm (from the center to the center of the target); and in another condition, they were required to move the cube within a distance of 40.8 cm, which served as an independent variable (IV1: simple and difficult). Further, the same participants moved a cube with an external focus instruction (EXF) in one condition and with an internal focus instruction (INF) in another condition, which served as another independent variable (IV2: EXF and INF). During the EXF condition, participants were told to, "*focus on moving the cube as accurately as possible."* The same participants during the INF condition were told to, "*focus on moving [their] arm as accurately as possible*." This design comprised participants performing the four separate conditions (*i.e.*, EXF-Simple, EXF-Difficult, INF-Simple, INF-Difficult). For each condition, participants performed two trials, where each trial consisted of 30 taps (15 taps on each target. To synchronize the movement to the metronome beeps, the first five taps were eliminated). Three reflective markers were attached to the cube and this was tracked by a 3D motion capture system (Qualisys, Göteborg, Sweden), captured at 200Hz. Dependent variables were accuracy (MRE, mean radial error), consistency (BVE, bivariate variable error), and bias (SRE, subject-centroid radial error). All data were analyzed using Matlab (R2017a, MathWorks Inc., Natick, MA).

First, our results replicated the previous work in the Fitts' Law paradigm (*e.g.*, Fitts, 1954) in that error increased in the longer distance relative to the shorter distance regardless of instructions. For accuracy, the EXF showed lower MRE relative to the INF conditions regardless of difficulty. Similarly, the EXF condition showed higher consistency (BVE) relative to INF regardless of difficulty. There was no difference in attentional focus instructions in bias. In summary, the study showed more proficient performance with an EXF instruction in the aiming task.

In another study (Yamada, Raisbeck, Diekfuss, & Kuznetsov, 2020), the task difficulty was manipulated by changing the movement speed. In one condition, participants moved the cube between targets at 80BPM, while they moved the same distance with 120BPM in another condition. This task was conducted in a Virtual Reality (VR) environment in one study and in the physical environment in another study (Figure 2.12). Regarding the performance in VR, our results showed an increased accuracy and consistency during the EXF condition relative to the INF condition regardless of the movement speed. However, when tested in the physical environment, there was no difference between the EXF and INF conditions.

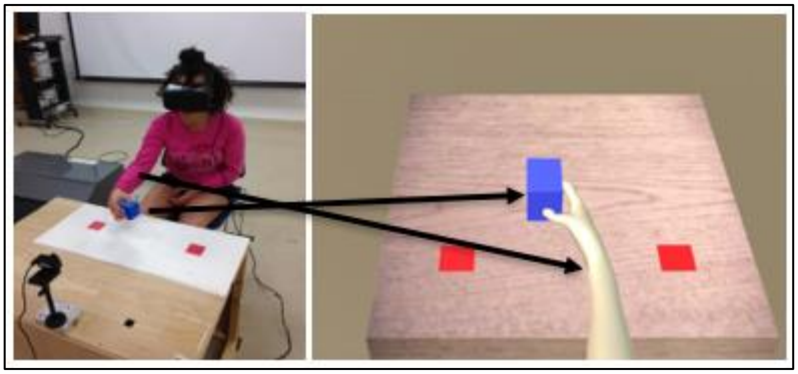


Figure 2.12. Fitts' Law Task in VR. Adapted from Yamada et al. (2019).

From these studies (Raisbeck et al., 2020; Yamada et al., 2020), some limitations surfaced. First, changing the task difficulty did not change the relationship of attentional focus effects, contrary to the previous findings (*e.g.*, Landers et al., 2005; Wulf et al., 2007). One potential explanation for the result was that restricting movement may have caused both simple and difficult conditions to be difficult (Raisbeck et al., 2020). Previous literature shows that movement speed naturally increased during the EXF condition (Ille et al., 2013; Porter et al., 2010; Vance et al., 2004 Exp.1). Thus, restricting movement speed served as a constraint that made the task more difficult. Secondly, even if the physical distance was twice as far between the simple and difficult conditions in Raisbeck et al. (2020), the actual difference in ID was only about 0.5. Therefore, it may require greater difference in ID's between conditions and freeing the movement speed in this task to investigate the task difficulty and attentional focus instructions. Additionally, the study design was suitable to minimize individual differences. However, for the within-subject design, learning effect was not tested. As a result, this study design was not suitable to examine the cognitive shift by practice (*i.e.*, the gaps (A)).

Summary

Motor learning and control theories have developed from the cognitive psychological view of the “executive center” control of motor learning and information theory. The present review also introduced a new paradigm, investigating behavioral change as self-organization interacting with constraints and examining underlying structure (*e.g.*, fractals) of times series variability.

Motor performance and learning specific to attentional focus was introduced. However, specific mechanisms regarding how attentional focus strategies influence motor control and learning is still unclear. The dynamic systems theory within the Fitts’ Law paradigm may be an alternative method to understand the underlying structure of motor control outside the mean and SD of performance, and thus may allow us to develop theories in attentional focus. Further, how attentional focus strategies influence motor learning and psychological profiles are still unknown, which may explain previous inconsistent findings.

In the series of our studies (Raisbeck et al., 2020; Yamada & Raisbeck, 2019; Yamada et al., 2020), the results indicate a potential benefit of an EXF in a Fitts’ Law task. However, the interaction of task difficulty effects by previous studies (Becker & Smith, 2013; Wulf et al., 2007) were not supported from these preliminary studies. Primary limitations of the Fitts’ Law and attentional focus studies (Raisbeck et al., 2020; Yamada & Raisbeck, 2020; and Yamada et al., 2020) were (1) the movement speed was restricted, (2) difference in the task difficulty between conditions may not have been sufficient, and (3) the results were comparative only to motor performance, not learning of the motor skill. The present dissertation work is devoted to understanding the factors—task difficulty and practice—that may influence the effect of attentional focus from multiple approaches.

CHAPTER III

METHODS

Participants

Sixty young adults will be recruited for the present study. Participants must 1) be older than 18 years-old and younger than 50-year-old, 2) have no existing injuries in the upper limbs, 3) have no previous injury or surgery in the past six months, and 4) be naïve to the task (*i.e.*, never participated in a research study using a reciprocal tapping task). All potential participants will complete an informed consent approved by the Institutional Review Board of the University of North Carolina at Greensboro (UNCG) (Appendix A). Upon the completion of participation, a course extra credit may or may not be provided depending on the course instructor's permission. Participants will be recruited through flyers, (Appendix B) and verbal recruitment by visiting courses offered at the UNCG main campus (Appendix C).

Procedures

The present study will be a mixed design with a three-day participation in which each day is separated by 48 hours (*i.e.*, Monday/Wednesday/Friday or Tuesday/Thursday/Saturday). On day 1, participants will complete the consent form, followed by initial screening including height, weight, age, gender, any injuries in the upper extremities or medications that may influence the results of the motor skill execution, and previous experience of a Fitts' Law task (Appendix D) and the Edinburgh Handedness Inventory-Short Form (Veale, 2014) to determine their hand-dominance (Appendix E).

Following the initial screening, six reflective markers will be placed on participants' upper body: Base of the second metacarpal, wrist, elbow, left shoulder, and right shoulder. The task that will be adopted for the present study is an aiming task, generally referred to as Fitts' Law task. In this task, participants move their finger or implement between targets and hit the targets as fast and accurately as possible. A similar task has been investigated in previous literature (Fitts, 1954; Fitts & Peterson, 1964; Woodworth, 1899). Participants will be asked to sit in a chair (45.72 x 46.99 x 43.18 cm, width x depth x height, respectively) on a table (69.85 x 76.45 cm). To minimize the trunk motion, participants will be asked to sit all the way back to the backrest of the chair and maintain contact with the backrest during performance. On the table, there are two targets that have a target area and error area and a pen (2 x 2 x 9 cm) (Figure 3.1a). These two targets are on top of platforms with rails so the distance between the targets can be adjusted. Additionally, the platform serves as a holder so a target varying its target area can be replaced. On the target, 1 x 1 cm cross mark is placed at the center of the target and the error areas of the target are aluminum plates (Figure 3.1b). These plates are wired through the platform, battery, LED light, and the bottom of the pen. When the bottom of the pen hits on the error areas, the LED light will turn on to provide participants with knowledge of results (Figure 3.1a).

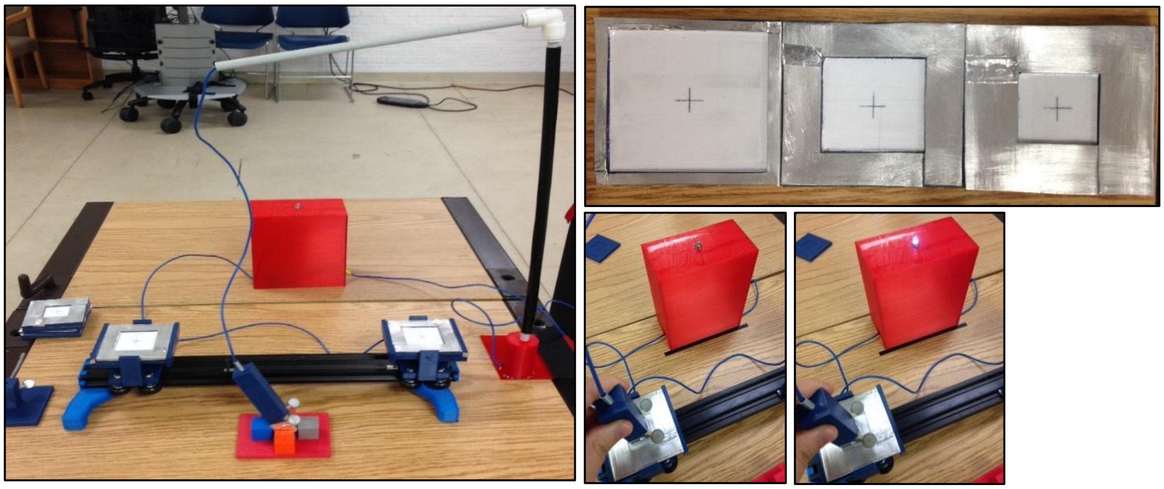


Figure 3.1. Experimental Setting. (Left) Platforms (two blue plastic squares) are stabilized on the black rail with wheels. Each platform serves as a holder for the targets that vary in size of the target area (top right). One end of the platform is surrounded by an aluminum plate. The aluminum materials of the platform are wired through an LED light (red box), 9V battery, and to the bottom of the pen (blue one in the middle). Thus, when the bottom of the pen hits on the targets, it completes a closed circuit, lighting the LED, which serves as knowledge of results for participants (bottom right).

Prior to a familiarization phase, participants will receive general instructions regarding the task, which includes 1) holding the top part of the pen from the side, 2) tap the pen perpendicular to the targets, 3) the task is to move the pen back and forth between targets, and 4) the goal of the task is to as many times as possible, aiming the center of the targets, while *emphasizing accuracy*. During the familiarization phase, participants will perform the task with their dominant hand. Each trial begins with a “ready” auditory signal (50ms tone) followed by a “go” signal after 500ms from the ready signal, using Arduino Uno (Arduino). After 30 seconds, another 50ms duration tone will be signaled, which serves an end signal. The data will be recollected when participants begin the movement prior to the second beep. A miss hit is defined as any side of the object touching outside of the targets (*i.e.*, the error area). The experimenter will count the number of error taps during data collection. When the number of error taps exceeds a pre-determined threshold, that trial will be recollected. The number of the thresholds was determined by measuring the average of error hits during a pilot data (*N* = 11). The average miss hits (SD) were 0.64 (1.43), 1.91 (2.17), and 7.23 (3.17), for the ID_{low}, ID_{med}, ID_{high}, respectively. We determined the upper 68.27% (1-point SD) point plus mean as the threshold for each error-hit threshold, which is 2, 4, and 10 taps for the ID_{low}, ID_{med}, ID_{high} conditions, respectively. If participants exceed this number of error taps, we consider that participants did not prioritize accuracy, and thus that trial will be recollected. Performance will be measured by tracking three reflective markers on the pen with a 3-D motion capture system (Qualisys, Gothenburg, Sweden) at 100Hz. Performance will be processed and measured following the data collection, using MATLAB (Mathworks, MA). To become familiar with the testing environment and understand the general instructions provided above, two trials that are within the error threshold will be practiced at the distance between targets of 16 cm. The target size will be 4 x 4 cm for the familiarization.

Following the familiarization phase, participants will perform the baseline. The study procedure is summarized in Figure 3.2. The baseline measure will begin with a perceived competence questionnaire. Participants will be asked (based on their experience on the familiarization trials) how well they think they will perform on the following task by a 7-point Likert Scale (Appendix F). The baseline consists of one 30-second trial with three difficulty (ID) conditions. The ID for each condition is 2, 4, and 6 for ID_{low}, ID_{medium}, ID_{high}, respectively (8, 16, 32 cm apart between targets with 6 x 6, 4 x

4, and 3 x 3 cm target areas, respectively). These ID's were calculated by a formula presented by Fitts (1954): ID = $\log_2(2D/W)$, where D represents the distance and W represents the target size (width). Since the tip of the pen has a dimension (2 x 2), ID was calculated by a tolerance limit. That is, 6 x 6 target area has a tolerance limit of 4 cm (6cm – 2 cm) in the medio-lateral direction. Thus, the ID_{low} was $\log_2[(2 \times 8) / 4]$. After one trial with each ID, participants will be asked, "*if there were any methods and techniques that you adopted, or any thoughts that are not related to the task, please report. If you weren't thinking about anything else, you do not have to answer the question,*" which is a part of the compliance check that participants will answer during the acquisition phase.

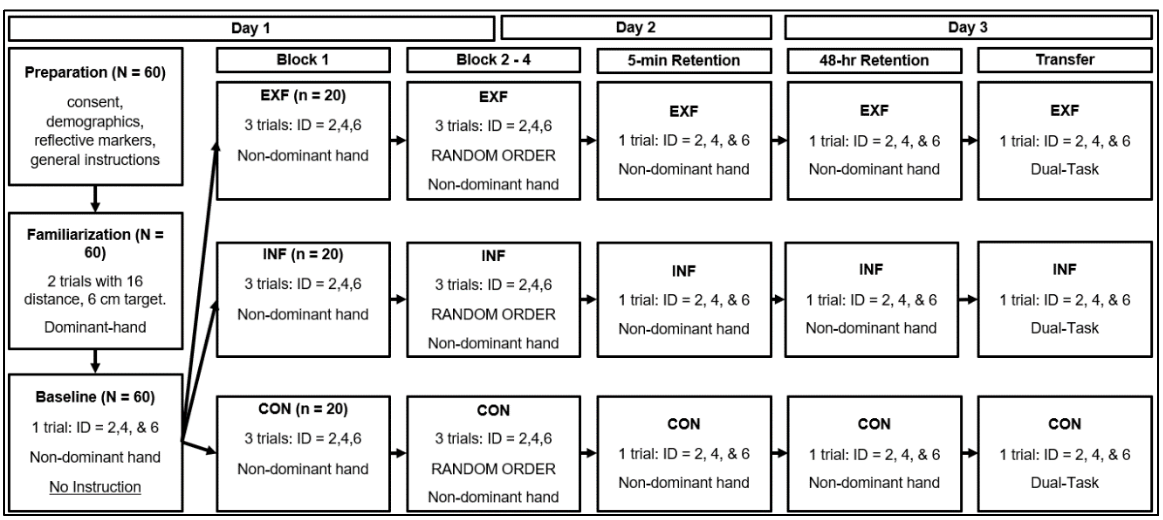


Figure 3.2. Experimental Procedure.

After one trial with each ID, participants will be asked to answer a questionnaire to assess their mental load, using NASA-TLX (Hart & Staveland, 1988) (Appendix G). Also, participants will be asked, "*if there were any methods and techniques that you adopted, or any thoughts that are not related to the task, please report. If you weren't thinking about anything else, you do not have to answer the question,*" which is a part of the compliance check that participants will answer during the acquisition phase. Then, a verbal fluency baseline test will be collected. This test will consist of naming as many animals as possible that begins with an A (including insects and type of breeds) during a 30-second trial.

The acquisition phase will follow immediately following the baseline. Participants will be randomly assigned to one of the following groups: control (CON), external focus (EXF), and internal focus (INF). They will be told to practice the task based on a specific instruction. This acquisition phase consists of practicing the same 3 ID's used in the baseline condition with their non-dominant hand. First, participants will receive an assigned instruction on a sheet of paper (Appendix H). The instruction for the EXF group will be, "*mentally focus on moving the pen as fast and accurately as possible*." The instruction for the IF group will be, "*mentally focus on moving your hand as fast and accurately as possible*." The instruction for the CON group will be, "*During practice, I want you to only think about doing your best.*" This instruction in a sheet of paper will be shown prior to the beginning of each ID condition. Prior to each ID condition, the perceived competence was assessed. Then, participants will perform three 30-second trials with one ID. Following the three trials, participants will be asked to answer the

NASA-TLX. Then, the compliance check questionnaire will be conducted (Appendix I), which consists of three questions: The first question asks, "*what was the given instruction?"* Participants will be asked to precisely repeat the given instruction, and the experimenter will record the responses. Then, the second question will be asked, "*how much were you able to follow the instruction?*" This question will be answered in a 7-point Likert Scale. The last question will be, "*In addition to the given instruction, if there were any methods and techniques that you adopted, or any thoughts that are not related to the task, please report. If you weren't thinking about anything else, you do not have to answer the question.*" Each question will be asked verbally while participants see the questionnaire on the table. Participants' answers will be audio-recorded and transcribed into a computer. This cycle will be repeated for the next ID condition. Thus, a total of nine trials is considered as one block with a brief rest interval between each trial. For the first block of the acquisition phase, all participants will practice three 30-seconds of the ID_{low}, three 30-second of the ID_{med}, and the ID_{high} condition, which match the order amongst the testing phases (*i.e.*, baseline, retention tests, and transfer test). For the second through fourth block, the order of the ID's will be randomized. On day 1, a total of two blocks (18 trials) will be practiced. On day 2, participants will revisit the lab and repeat the same acquisition procedure from day 1 for two blocks, which will result in a total of 36 acquisition trials for the present study. Following this procedure, a 5-minute-delayed retention test will be performed with the same procedure as the baseline. During this phase, the same attentional focus instructions will be provided. The questionnaires will be the same as the acquisition phase: Prior to trials with each ID, a perceived competence questionnaire will be asked. Following the trials, the NASA-TLX and compliance checks will be collected.

On day 3, participants will revisit the lab and be informed to perform with an assigned instruction that they adopt during practice. Then, the exact same procedure of the 5-minute delayed retention test will be conducted: One 30-second trial of ID_{low}, ID_{med}, and ID_{high} which serves as the 48-hour delayed retention test. Following the retention test, a 2-minute rest will be provided, and participants will be informed that they will be performing the same task but with another task performing simultaneously as a transfer test (*i.e.*, a dual-task procedure). The secondary task will be the verbal fluency task. One trial for each ID will be collected. All participants will be asked to name as many animals starting with C for ID_{low}, G for ID_{med}, and P for ID_{high}. The data will be tape-recorded for the following analysis of the secondary task performance. Again, following each ID, NASA-TLX and compliance will be collected.

Data Processing

Collected data will be first filtered using MATLAB (Mathworks, MA) with a Savitzky-Golay filter (r = 1, m = 9). The filtration method was chosen by qualitatively examining the residuals and normality from previous studies (Raisbeck et al., 2020; Yamada & Riasbeck, 2020). Velocity of the object is measured by examining the second derivative of the displacement of the right forward (RF) marker on the object in the z-axis (vertical direction). Taps on the targets are calculated with a findpeaks function of MATLAB of the RF marker. The same method is adopted for body markers (wrist, elbow, shoulder). The spatial accuracy of measurement was assessed by a five-second static trial., which showed SD = 0.02 mm in x, y, and z axes from the RF marker position. Three additional markers will be placed on the three corners of each target to calculate the center of the target.

Performance

The primary dependent variable is movement time (MT). MT is measured as the number of taps divided by the duration of each trial (*i.e.*, 30sec). Additionally, the number of error taps will be measured. To measure precise spatial accuracy, the center of the pen and targets will be determined by calculating marginal points of a midpoint of two horizontal markers (*i.e.*, RF) and perpendicular markers (*i.e.*, left forward and left forward and left back) of the reflective markers on the object and targets. Two-dimensional accuracy and variability from the center of the targets and the center of the object will be calculated (Hancock et al., 1995). Specifically, accuracy will be measured as Mean Radial Error (MRE), which represents the general accuracy by measuring the direct distance from the center of the target to the center of the pen, and its variability (BVE, bivariate variable error). MRE and BVE will be described to show spatial accuracy.

Dual-Task Cost

Dual-task will be analyzed by (1) analyzing the number of answers provided for the secondary task and (2) analyzing the dual-task cost (McCulloch, 2007):

Dual task cost = (Single task – dual-task performance) / single task performance * 100

In the present study, the design is a mixed design. Thus, the single task performance that will be compared with the dual-task performance will be the performance during the 48-hour retention test.

Sample Entropy and CV

For study 2, sample entropy will be measured for continuous time series of angular velocity. Additionally, CV of the joint displacement and angular displacement will be measured for movement variability measures.

Subjective Measures

Mental load will be determined by calculating the results of NASA-TLX. NASA-TLX consists of six questions asking 1) mental demand, 2) physical demand, 3) temporal demand, 4) performance, 5) effort, and 6) frustration in 20-point (0 as low and 20 as high). When the data is represented, it is represented as 0 - 100 (by multiplying by five). The total scores divided by the number of questions will be used for statistical analyses (Diekfuss & Raisbeck, 2017).

For the compliance check, the first question asked, "*what was the given instruction provided in the paper?*" will be analyzed if the participants provided a correct answer by sorting "yes" or "no." For the correct answers, the next question, "*how much were you able to follow the given instruction?*" will be analyzed. This question will be answered in a 7-Likert Scale in 1 as "not at all" and 7 as "always." The score of the "degree" of compliance will be analyzed (Raisbeck et al., 2020). The third question is asking for the explicit rules (*i.e.*, declarative knowledge), asking any thoughts or strategies that participants adopted during performance in addition to the given instruction. The answers will be categorized by INF, EXF, task-irrelevant, the goal of the task, or else. Also, the number of rules listed by participants will be analyzed.

Perceived competency is measured with a 7-point Likert Scale asking, "*how do you think you will perform on the follow-up task?"* (Conroy, Coatsworth, & Fifer, 2005), which was adopted in the study by Frikha et al. (2019). The dependent variables are summarized in Table 3.3.

Statistical Approach

Study One

For study one, the dependent variables will be analyzed between baseline and retention tests with 3 (Group) x 3 (ID) x 4 (Baseline; two retention tests and transfer) ANOVA with repeated measures on the last two factors will be conducted. The practice phase will be analyzed using a 3 (Group) x 3 (ID) x 4 (Block) ANOVA with repeated measures on the last two factors. Additionally, 3 (Group) x 3 (ID) ANOVA with repeated measures on the second factor will be analyzed for the dual cost during the transfer test. Alpha will be $p < .05$ for all analyses *a priori*. *Post hoc* tests will be conducted with ANOVA for a three-way interaction and pairwise comparisons (t-tests) for appropriate factors. The type I error in the *post hoc* will be controlled using False Discovery Rate.

Study Two

For study two, a coefficient of variation (CV) and sample entropy will be analyzed with 3 x 3 x 4 ANOVA for the testing phase and 3 x 3 x 4 ANOVA during practice. In the transfer, 3 (Group) x 3 (ID) ANOVA with repeated measures on the second factor will be conducted. For comparison with performance and movement and time series variability, the same dependent variable used in Study 1 will be used (MT). Alpha will be set at .05 for all analyses *a priori*. *Post hoc* tests will be conducted with ANOVA for a three-way interaction and pairwise comparisons (t-tests) for appropriate factors. The type I error in the *post hoc* tests will be controlled using False Discovery Rate.

Study Three

For study 3, subjective profiles will be analyzed using a 3 x 3 x 4 (Block) ANOVA with repeated measures. However, for the compliance and explicit knowledge, there will be no questionnaire provided during the baseline. Testing phase will be analyzed using 3 x 3 x 4 ANOVA with repeated measures. Alpha will be $p < .05$ for all analyses *a priori*. *Post hoc* tests will be conducted with ANOVA for a three-way interaction and pairwise comparisons (t-tests) for appropriate factors. The type I error in the *post hoc* will be controlled using False Discovery Rate.

Descriptive Measures

MRE and BVE will be described to present the precise spatial accuracy of performance (reported in Manuscript II).

Disclaimer

Since participant recruitment was not possible during summer (between the dissertation proposal and the beginning of data collection) and shutdown of the campus due to COVID-19, I have used these periods to further strengthen and develop the validity of the dissertation. In these periods, I have learned several important modifications that would make better interpretation of the results. The following modifications were made for the final version of the manuscripts.

1) Statistical Analysis: In Chapter III, the main statistical analysis for motor learning effect was proposed to use 3 (Group) x 3 (ID) x 4 (Test) ANOVA with repeated measures on the last two factors. However, the transfer test introduces a new factor (*i.e.*, dual task), which makes it incompatible with the results of the other testing phases. Therefore, the testing phase was analyzed separately using a 3 (Group) x 3 (ID) x 3 (Test) ANOVA with repeated measures on the last two factors, and the transfer test was measured 3 (Group) x 3 (ID) ANOVA with repeated measures on the second factor. Further, for Chapter V (Manuscript II), the main analysis for variability was 3 (Group) x 3 (ID) x 3 (Test) ANOVA. However, to see the interaction between the joints, it has been modified to be a 3 (Group) x 3 (ID) x 3 (Test) x 3 (Joint) ANOVA.
2) Statistical Analysis for the practice: In a traditional motor learning research, a single task is tested across the time factor. However, in the present study, participants practiced three different task difficulties and practiced three trials for each difficulty. As a result, there is a time factor within each difficulty, another

time factor between different difficulties. These two-time factors are wrapped in the experimental time factor (see below). Therefore, a multi-level model analysis would be appropriate, and ANOVA may not lead to an appropriate interpretation of the results. Further, the primary purpose of the present study is a learning effect. Consequently, the present study ran the statistical analysis using ANOVA as proposed; however, practice results were not included in the discussion.

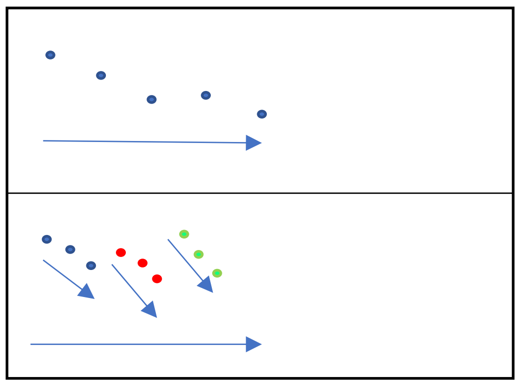


Figure 3.3. Multi-Level Factors. Top figure represents a typical experimental design where participants practice one task; the figure below represents the present study: Participants practice multiple trials (one time factor that can correlate) of three different tasks (another time factor that can correlate). These factors are wrapped in the overall time factor, which hypothetically produces a zigzag improvement when examining the overall time factor. This hinders the ability to interpret the exact learning effect and produces different interpretations from the testing phase (testing phase consists of one trial).

3) Due to the results of 2), performance results during practice are reported in the manuscript, but the hypotheses regarding the practice effect were excluded in the main manuscripts. The original hypothesis was to compare the results between the baseline and Block 1 of the acquisition phase to measure the immediate effect, and this result was planned to be compared with the learning effects (between baseline and retention tests). However, the testing phase consisted of one trial

while the acquisition phase consisted of three trials, which makes the comparison difficult.

4) Transfer test: In manuscript I (Chapter IV), the effect of automaticity was measured using DTC. However, dual- "cost" implies that a higher value indicates a greater "cost" of dual task procedure. To represent this, higher values of the dependent variables need to implicate greater performance. However, for MT, higher value indicates poorer performance. This creates confusion between the term and the values. Therefore, the following formula was adopted for the present study:

Dual Task Cost = {(Single task – dual-task performance) / single task performance * 100} * (-1)

5) *Post hoc* tests: In the proposal, *FDR (False Discovery Rate)* was planned to use. However, FDR is generally used for hundreds of dependent variables of *the same research question*. In the present study, although a considerable number of dependent variables are used, these variables are used with different research questions in different manuscripts (see below). As a result, using adjusted p-values based on FDR on multiple studies may not be appropriate. Consequently, the type I error in the *post hoc* tests will be controlled using Bonferroni correction.

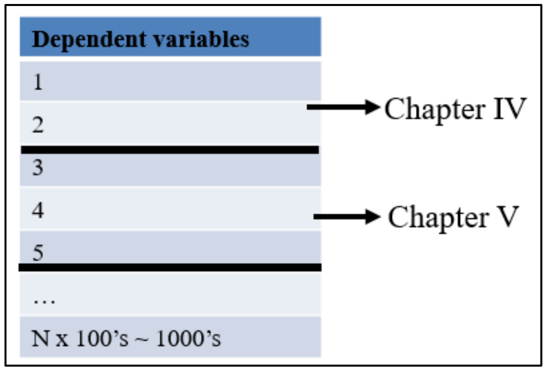


Figure 3.4. Control of Type I Error

6) Chapter V: The dependent variables for Chapter V were proposed to be Sample entropy and CV of joint angular velocity. However, the rationale for using movement variability was based on Verejiken et al. (1992), which adopted SD of joint angle. Therefore, in addition to the proposed variables, the manuscript included SD of the angular velocity for comparison.

CHAPTER IV

THE EFFECTS OF TASK DIFFICULTY AND THE RELATIONSHIP BETWEEN EXTERNAL FOCUS, INTERNAL FOCUS, AND NON-ATTENTIONAL FOCUS STRATEGY

Abstract

Attentional focus research has demonstrated the beneficial effects of an external focus (EXF) over an internal focus (INF). However, studies (Landers et al., 2005; Wulf et al. 2007) have shown task difficulty may affect the attentional focus effects, and the existing theory (*i.e.*, the constrained action hypothesis) proposes an EXF benefit *and* INF detrimental effect, although there have been no consistent results when compared to a non-attentional focus strategy (control, CON). Poolton et al. (2006) proposed that an INF affects information processing by disrupting working memory. Therefore, the present study investigated how task difficulty influences the attentional focus effects and the relationship between EXF, INF, and CON. Sixty healthy young individuals were assigned to an EXF, INF, or CON group and practiced a Fitts' reciprocal tapping task that varies in three difficulty (ID = 2, 4, and 6) for two days. Movement time (MT) during a 30s trial and the number of error taps were measured for each ID in the baseline, 5-minute, and 48-hour retention tests. Additionally, the degree of automaticity was measured in the transfer test following the 48-hour retention test by a dual task procedure. Results showed

that all groups decreased MT and error with no group difference in the retention tests. Further, there was no evidence of task difficult influence on attentional focus. However, the magnitude of improvements was more evident in the most difficult condition. Interestingly, the INF group showed a trending difference with a medium effect size ($F_{2, 57} = 3.10$, $p = .053$, $\eta^2_p = .10$) relative to the CON group in the transfer test. Our results suggest that there is an INF disruptive effect rather than EXF benefits *and* INF effects. The effect of task difficulty and attentional focus is discussed in detail.

Introduction

When performing motor skills, there are multiple environmental and internal relevant or irrelevant cues, therefore it becomes critical to distinguish which cues are important for motor skill acquisition (Gentile, 2001). The overall arching goal in motor behavior is to determine an optimal level, regardless of the area. This has shown to be true for research centered around determining an optimal attentional focus (Beilock & Carr, 2001; Singer, Lidor, Cauraugh, 1994; Wulf, 2013). Earlier research in attentional focus has shown that a slight manipulation of attentional focus between *task-relevant* cues resulted in a profound difference (Wulf et al. 1998). Wulf et al. showed that directing an individual's attention to the effects of movements on the environment (external focus, EXF) was superior to directing attention to body movements (internal focus, INF). This benefit of an EXF over INF has been demonstrated in a variety of motor skills that require: accuracy (Lohse et al., 2010; Hitchcock & Sherwood, 2018; Marchant et al., 2007; Raisbeck et al., 2019; Zachry et al., 2004), muscular strength (Ducharme et al., 2015; Marchant et al., 2009; Wulf et al., 2011), and balance

(Chiviacowsky et al., 2010; Landers et al., 2005; Wulf et al., 2007; McNevin et al., 2003; Wulf et al., 2001). An accepted hypothesis that explains the attentional focus effects is the constrained action hypothesis (CAH) (McNevin et al., 2003; Wulf et al., 2001a; 2001b). The CAH proposes that an INF disrupts the motor system by disrupting neuromuscular control (Lohse, 2012; Lohse et al., 2010; Marchant et al., 2011) and an EXF promotes a more automated mode of process (McNevin et al., 2003; Wulf et al., 2001a, 2001b). The rationale of the EXF benefits is that motor output is organized by an intended effect rather than referring to the spatiotemporal pattern of movements (Wulf et al., 1998), which was adapted from the action effect hypothesis (Prinz, 1992, 1997). Empirical evidence has shown that performing a balance task while simultaneously performing a secondary probe reaction time task was better with an EXF than performing the same dual task with an INF (Kal et al., 2013; Wulf et al., 2001). Since greater performance under a dual task has been suggested to be indicative of a more automatic process of information (Abertney, 1999), an EXF may promote a fast and reflexive process (Wulf et al., 2001), leading to greater performance. Evidence of a disruptive effect of an INF is abundant in studies that examined neuromuscular control, using electromyography (EMG). Studies have shown that an INF increased the neuromuscular activities but resulted in a poorer force production (Marchant et al., 2009), dart throw (Lohse et al., 2010), basketball shooting (Zachry et al., 2004), and vertical jumping performance (Wulf et al., 2011). These studies presented inefficient motor coordination when using an INF (Lohse 2012; Greig & Marchant, 2014).

While the benefits of an EXF is robustly established (Wulf, 2013 for a review), other studies have revealed task difficulty may be a factor that may change the attentional focus effects. Landers et al. (2005) found that Parkinson's disease patients benefited from an EXF only during a challenging postural control task. This task difficulty interaction was replicated in healthy young adults (Becker & Smith, 2013; Wulf et al., 2007). Task difficulty is also affected by the skill level of the performer. Since skill is *relative* (Logan, 1985), task difficulty possesses both absolute and relative aspects. That is, riding a bicycle is more difficult than riding a tricycle in an absolute term, however, experienced adults would not perceive riding a bicycle as difficult compared to a child who just transitioned from a tricycle to a bicycle. Thus, when difficulty of motor skills is affected by the nature of the task and experience. Research examining the relative aspect of difficulty has shown that simply telling experienced individuals to "*do your best*" was superior to both EXF and INF (Porter & Sims, 2008; Wulf, 2008). These studies are in line with the previous findings examining the absolute aspect of difficulty (*e.g.*, Landers et al., 2005; Wulf et al., 2007) since performing a balance task is "easy" for a professional acrobat (Wulf, 2008) due to experience. Although some studies showed the EXF benefits regardless of task difficulty (Aloraini et al., 2019; Raisbeck et al., 2019) or in both novices and experienced individuals (Asadi, Farsi, Abdoli, Seami, & Porter, 2019; Halperin, Chapman, Martin, Abbiss, 2017; Wulf et al., 2002), task difficulty may serve as a moderating factor for the attentional focus effects. Although the CAH proposes a universal benefit of EXF, a limitation exists that it does not account for task difficulty. Therefore, research continues to develop the attentional focus theories, Poolton et al.

(2006) proposed that an INF induces more explicit rules thus increasing the consumption of *working memory* indicating attentional focus influences information processing. The information processing theory (*e.g.*, Fitts & Posner, 1964; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977) propose that the efficiency of information process changes by situations (*e.g.*, novelty and salience of stimuli). For example, when an individual learns a novel, unfamiliar, or difficult skill, it requires a large portion of attention; Thus, he/she processes information more slowly and consciously, known as a *controlled process*; Contrary, when the task is easy, little attention is required, which does not consume a online process (working memory), known as an *automatic process* (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Although Poolton et al. did not find a difference in the amount of explicit knowledge between EXF and INF, the INF group resulted in a greater number of body-related, task relevant thoughts. An advantage of the information process framework is that it may explain task difficulty interaction. Applying this supports previous research suggesting that EXF promotes automaticity and INF disrupts this process. Accordingly, when performing a task that an individual perceives to be easy based on their skill level and automatic process is adopted (Landers et al., 2005) acrobats (Wulf, 2008). In this situation, an attentional focus intervention may not be helpful and simply thinking to do best may be optimal since the characteristics of the information process in this situation is using little attentional resources. Contrary, when a task is too difficult, individuals may not be able to process a given attentional focus cue due to overload of attentional capacity. Thus, the effects of attentional focus strategies may be evident when individuals require a controlled process where the task is not too difficult or easy. Therefore, the information processing theory may provide a better explanation for both previous findings showing the EXF benefits and findings that did not find the EXF benefits.

Another theoretical concern of the CAH is that it indicates bidirectional effects: An EXF is effective and INF is detrimental to motor learning and motor skill performance. For this hypothesis to be valid, an EXF requires to be superior to a non-strategy (*i.e.*, control or CON) *and* INF must be inferior to CON. However, a lot of studies that supported the CAH did not include a CON condition (Wulf et al.,2001a, 2001b, McNevin et al., 2003; Marchant et al., 2007; Zachry et al., 2005). Consequently, it is unclear whether an EXF is superior, an INF is inferior, or both (Hodges & Ford, 2007). Although Wulf (2007) argued that there is abundant evidence showing that an EXF is superior to a CON, some studies showed that EXF was not different from CON (Marchant et al., 2007; Stoate & Wulf, 2011; Winkelman et al., 2017), therefore the results are inconsistent. Further, Wulf (2007) suggests that an INF and CON will be the same, implying a unidirectional effect (*i.e.*, only EXF affects motor performance). Although the relationship between EXF and INF is well established, the relationship among EXF, INF, and CON is still unclear. Considering empirical evidence that showed a non-attentional focus strategy may be beneficial than attentional focus strategies in some cases (Beilock & Carr, 2001; Porter & Sims, 2008; Potvin-Desrochers, Richer, & Lajoie, 2017; Wulf, 2008), including a CON condition is necessary to investigate the directionality of attentional focus effects.

In the present study, participants were assigned to one of three groups (EXF, INF, or CON) and practiced an aiming task that varied in task difficulty. Three hypotheses were stated (A: Task difficulty; B: Relationship between EXF, INF, & CON; C: Transfer test) with subparts (1 & 2) of hypotheses were established regarding the attentional focus effects, using the information process theory. A.1) When a task is *easy*, the CON group would be superior to the INF and EXF groups, and A.2) when the task is too difficult, the individual's working memory would be fully exploited. Thus, an EXF benefit exists when the task is not too easy or difficult (*i.e.*, moderately difficult task). B) The EXF group would perform better compared to the INF and CON, and the INF group would perform poorer than the EXF and CON groups; and C) moreover, due to the efficient mode of process by an EXF, the effect of attentional focus would be emphasized in a transfer task when participants' working memory are loaded under a dual task procedure.

Methods

Participants

Sixty healthy young adults participated in the study and were randomly assigned to one of the EXF (M_{age} = 22.45, SD = 4.15), INF (M_{age} = 22.95, SD = 4.14), and CON (M_{age} = 23.55, SD = 5.17) groups. Participants were recruited through emails and flyers posted in the public areas of the main campus of the university. Exclusion criteria were: Individuals who 1) are younger than 18 or older than 50 years-old, 2) sustain injuries or surgery in the upper extremities in the past six months, and 3) have had experience in the task. Hand-dominance was determined with Edinburgh Handedness Inventory-Short Form (Veale, 2014). Fifty-four participants were defined as right-handed and six were defined left-handed. All participants completed an informed consent approved by the institutional ethics committee.

Task and Apparatus

The task used in the present study was a Fitts' reciprocal tapping task (*e.g.*, Fitts, 1954; Raisbeck et al., 2019; Salmoni & Mcilwain, 1979; Sasangohar, MacKenzie, & Scott, 2009). Participants moved a stylus (2 x 2 x 9 cm) back and forth between two targets for 30 seconds. The task was performed while sitting in a chair (45.72 x 46.99 x 43.18 cm, width x depth x height, respectively) in front of a table (69.85 x 76.45 cm, width x height). On the table, two movable platforms were attached on a 40 cm rail (Figure 3.1a). Targets that vary in the *target area* can be replaced so the distance and size of the targets are manipulated. The dimension of the target was 70 x 70 x 9mm (Figure 3.1b) that varies in target area (*i.e.*, 60 x 60, 40 x 40, or 30 x 30 mm). A crosshair (10 x 10 mm) was marked at the center of each target area. The area outside the target area was surrounded by the *miss-hit area*. When participants hit the miss-hit area, an LED light turns on, providing the knowledge of results about error hits. Task difficulty was calculated as Index of Difficulty (ID): ID = $\log_2$ (2D/W) (Fitts, 1954; Fitts & Peterson, 1964), where D represents the distance and W represents the size (*i.e.*, width) of the targets. For the present study, W was calculated by the remaining space of the target area (*i.e.*, tolerance limit). For example, for the 60 x 60 mm target size, W was considered as 40mm (target width –stylus width = 40 mm). During the experimental procedure, trials with a 60 x 60mm target area at the distance of 80 mm (from the center of one target to the center of the other target) were defined as the easy conditions (ID_{low}), trials with a 40 x 40 mm target area and 160 mm apart were defined as the moderately difficult conditions (ID_{med}), and trials with a 30 x 30 mm area and 320 mm apart were determined as the difficult conditions (ID_{high}). The ID_{low}, ID_{med}, and ID_{high} conditions correspond to an ID of 2, 4, and 6, respectively. To record the moment of hit on the targets, reflective markers were attached to the stylus and tracked by a 3D motion capture system (Qualisys, Sweden). The data were collected at 100 Hz sampling frequency. Auditory signals were introduced three times as a ready, start, and end signal. The ready signal (500 ms duration tone) was presented followed by a 500 ms interval. Then, a start signal (50 ms duration tone) was presented. Following a 30-second trial, an end signal (50 ms duration tone) was presented. The data were post-processed with MATLAB software (Mathworks, MA). Although participants were able to see the light, the number of error taps were reported every after trial.

The handedness questionnaire (Edinburgh Handedness Inventory-Short Form) was completed, questions included, "*which hand do you use when you use*…", "*a pen*", "*a spoon*", "*a toothbrush*", and "*throw a ball*" at the beginning of the experiment. Each question was answered as "*always righ*t (100 points)", "*usually right* (50)", "*both* (0)", "*usually left* (-50)", and "*always left* (-100)" (Veale, 2014). The sum of the four scores divided by four was calculated, and the scores from -100 to -61 were defined as left-handed, from -60 to 60 were defined as mixed-handed, and from 61 to 100 were defined as right-handed. A manipulation check, asking "*what was the given instruction (in the white sheet)?*" was administered for three times following each block during the acquisition phase for a total of 12 times (3 difficulty x 4 blocks), and for nice times during the retention tests and transfer test (3 difficulty x 3 tests).

Procedure

The procedure is summarized in Figure 3.2. Participants were informed of the general protocol and asked to sit in a chair as close to the edge of a table to minimize the trunk motion. Participants were asked to hold the top part of a stylus from the side with three or four fingers. Then, they were informed, "*the task is to move a stylus back and forth between two targets during a 30-second trial*", and "*the goal of the task is to aim at the center of the targets as many times as possible, but emphasizing accuracy.*"; Additionally, all participants were informed to 1) wait for the start signal while holding the stylus on the right target, 2) begin the movements only after the start signal, 3) hit the targets with the stylus as perpendicular to the targets as possible, 4) continue to reciprocally move back and forth even if they made an error or missed tapping the target, and 5) that they may need to perform additional trials if they made more errors than a predetermined number of errors (*i.e.*, error limit). All participants were informed not only to hit on the target but to aim at the center of the target.

Prior to the baseline, participants were given two 30s familiarization trials with an ID of 3 using their dominant hand. During this phase, the emphasis was placed on understanding the general rules mentioned above. It was determined, *a priori*, that one additional trial would be given if participants did not understand the procedure. None of the participant did not perform a third trial.

Following the familiarization trials, participants performed one baseline trial which was a 30s trial with three levels of difficulty: ID_{low}, ID_{med}, and ID_{high} in the order of the low ID to high ID conditions. The error limits for each ID were 2, 4, and 10 taps for ID_{low}, ID_{med}, and ID_{high}, respectively. These error limits were predetermined from a pilot study (N = 11) by assessing the general number of errors for each ID. Participants were reminded of the goal of the task and performed the trials with their non-dominant hand. If participants began the movement prior to a start signal or exceeded the error limit, that trial was recollected. To minimize the variation in the total number of trials across participants, the maximum number of trials during the baseline for each ID was determined *a priori* as three trials. If participants did not perform each condition below the error limit within three trials, it was considered that the participant is incapable of performing or complying with the general rules, and thus excluded. None of the participants exceeded three trials.

Following the baseline, participants were randomly assigned to one of the external focus (EXF, n = 20), internal focus (INF, n = 20), and control (CON, n = 20) groups. The goal of the task was reminded, and participants were informed of the importance of complying with the instructions (attentional focus instructions) that they would receive. Participants in the EXF group were shown a white sheet of paper, as well as verbally told, "*mentally focus on moving the pen as fast and accurately as possible*". The instruction for the INF group was, "*mentally focus on moving your hand as fast and accurately as possible*", and the instruction for the CON group was, "*mentally focus only on doing your best"*. The instruction was provided in a piece of paper to distinguish it from other general rules provided during the familiarization phase, and then verbally given prior to each trial. The acquisition phase consisted of four blocks of nine trials of three consecutive trials of ID_{low}, three trials at ID_{med}, and three trials at ID_{high}. On Day 1, participants performed two blocks, with the order of Block 1 from a low to high ID. For Block 2, the order of ID's was randomized. On Day 2, participants revisited the lab and completed two additional blocks with the randomized order of ID's. Throughout the experiment, the same error limits (2, 4, and 10 for ID_{low}, ID_{med}, and ID_{high}, respectively) were used regardless of participants' performance.

For each ID, at least two trials below the error limit were collected. If participants exceeded the error limits for two trials out of the first three trials, an additional trial was collected until the second trial below the error limit was collected. The maximum number of the total trials for each ID were determined *a priori* as five trials to maintain the number of practice trials relatively the same across participants. Participants were excluded if they were not capable of performing two trials below the error limit by the fifth trial.

Following the fourth block, participants received a 5-minute sitting rest and performed a 5-minute delayed retention test with the same assigned instructions during the acquisition phase. Participants performed one 30-second trial for each ID from lowest to highest ID's. On Day 3, participants completed a 48-hour retention test with the same procedure of the 5-minute retention test. Following the 48-hour retention test, participants completed a dual task transfer test. The transfer test required participants to perform the task while naming as many animals as possible starting with a given alphabet letter.

Participants performed one 30s trial from low to high ID with C, P, and G, respectively. All participants completed the experiment on either Monday/Wednesday/Friday or Tuesday/Thursday/Saturday schedule.

Data Analysis

Data was processed by MATLAB, before and after the start and end signals were eliminated. Missing data were interpolated with spline interpolation function of MATLAB. If data were missing around the moment of hits on targets, the trial was excluded. Then, the data were filtered using a Savitzky-Golay (SG) filter (r = 1, m = 9). The parameters r and m were determined from pilot data (*N* =11) by qualitatively examining the residual plot, assessing normality, and superimposing the raw data over the filtered data. The spatial accuracy of measurement was determined by a 5-second static trial, and this was 0.02 mm SD in the x, y, and z axis, using the top right marker. The instant of hits was measured by tracking one of the markers on the stylus (a marker on the top left corner). The marker in the z axis (vertical position) is tracked during each trial. First, ranges approximately around the moment of hit (bottom parts of the sinusoidal movements) were identified. Then, the lowest value within each range was determined. This was considered as the moment of hit. Trials were excluded if participants double tapped the same target and unable to determine the true hit, participants began the movement prior to the start signal, or if there were too many missing data, especially around the moment of hits. Performance was measured as Movement Time (MT), which was calculated as the number of hits divided by 3000ms. Performance during the transfer test was determined as the dual-task cost (DTC) (Kal et al. ,2013, 2015; McCulloch, 2007): *DTC* = (single task performance - dual task performance) / single task performance x 100%. The performance of the 48-hour retention test was used for the single task and performance during the transfer test was used for dual-task performance. In the previous studies (Kal et al., 2013, 2015; McCulloch, 2007), a higher score indicated a greater performance, and thus higher DTC indicated a greater cost of a secondary task. However, a lower value represents a better performance for MT. Accordingly, the present study used:

DTC = [(single task - dual task) / single task x 100%] x (-1)

To show that a higher DTC represents a greater cost of a secondary task, and the value closer to zero indicates no influence of a secondary task.

Statistical Analysis

To measure the effect of attentional focus, a 3 (Group) x 3 (ID) x 3 (Time: Baseline; 5-minute retention; 48-hour retention) ANOVA with repeated measures on the two latter factors was used to measure MT and the number of errors. For MT, the DTC was used to measure the effect of dual task with a 3 (Group) x 3 (ID) ANOVA with repeated measures on the last factor during the transfer test. In the same manner, 3 (Group) x 3 (ID) ANOVA with repeated measures on the last factor was used for the number of error taps during the transfer test.

During the acquisition phase, participants practiced three trials for each ID with random order compared to the testing phase in which participants performed one trial for each ID in a specific order. During the acquisition phase, a time factor within each ID (learning effect; fatigue effect by repeating the same ID trials multiple times) is wrapped in another time factor between different ID conditions (learning effect by the acquisition phase procedure). Due to these differences between the acquisition and testing phases, the acquisition phase was analyzed using 3 (Group) x 3 (ID) x 4 (Block) ANOVA with repeated measures on the last two factors, but the results of the acquisition phase were excluded from the discussion.

Alpha was set at .05 *a priori* for all analyses. *Post hoc* tests were conducted if necessary, using Bonferroni correction at alpha level of .05. When there was a violation of sphericity in the main analyses, a Greenhouse-Geiser correction was used to interpret the results. Since p-value alone does not provide enough information to support hypotheses (Wasserstein & Lazar, 2016), the discussion and conclusion will be based on both p-value and effect size (Sullivan & Feinn, 2012). Effect size were qualitatively interpreted as partial eta (η^2_p) = .011 to .05 as small, .06 to .13 as medium, and > .14 as large (Cohen, 1988). Effect size ≤ .01 is interpreted as N/A since it is negligible effect size.

Results

Acquisition Phase

Movement time

The changes in performance throughout the experiment by group is shown in Figure 4.1. The mean and SD of MT and the number of taps during the acquisition phase is summarized in Appendix J. The results of MT showed a significant difference in ID ($F_{1.10,62.67} = 899.83$, $p < .01$, $\eta^2_p = .94$) and time ($F_{2.13,121.21} = 8.04$, $p < .01$, $\eta^2_p = .12$).

Post hoc tests confirmed that the ID_{low} was greater in MT than the ID_{med} and ID_{high} conditions ($p < .01$), and the ID_{med} condition was greater than the ID_{high} condition ($p < .01$). For *post hoc* tests of time, Block 1 was higher in MT than Block 2 ($p < .05$), 3, and 4 ($p < .01$), but no other differences were found. While no other differences are found ($p > .05$), there was a trending difference with a medium effect in interaction of time by groups ($F_{4.25, 130.46} = 2.28$, $p = .06$, $\eta^2_p = .07$). Figure 4.2 shows the marginal mean of time by group interaction (the marginal mean of different ID's, thus it ignores the different patterns of ID's), suggesting the pattern of improvements were qualitatively different by groups with similar performance at the end of the acquisition phase.

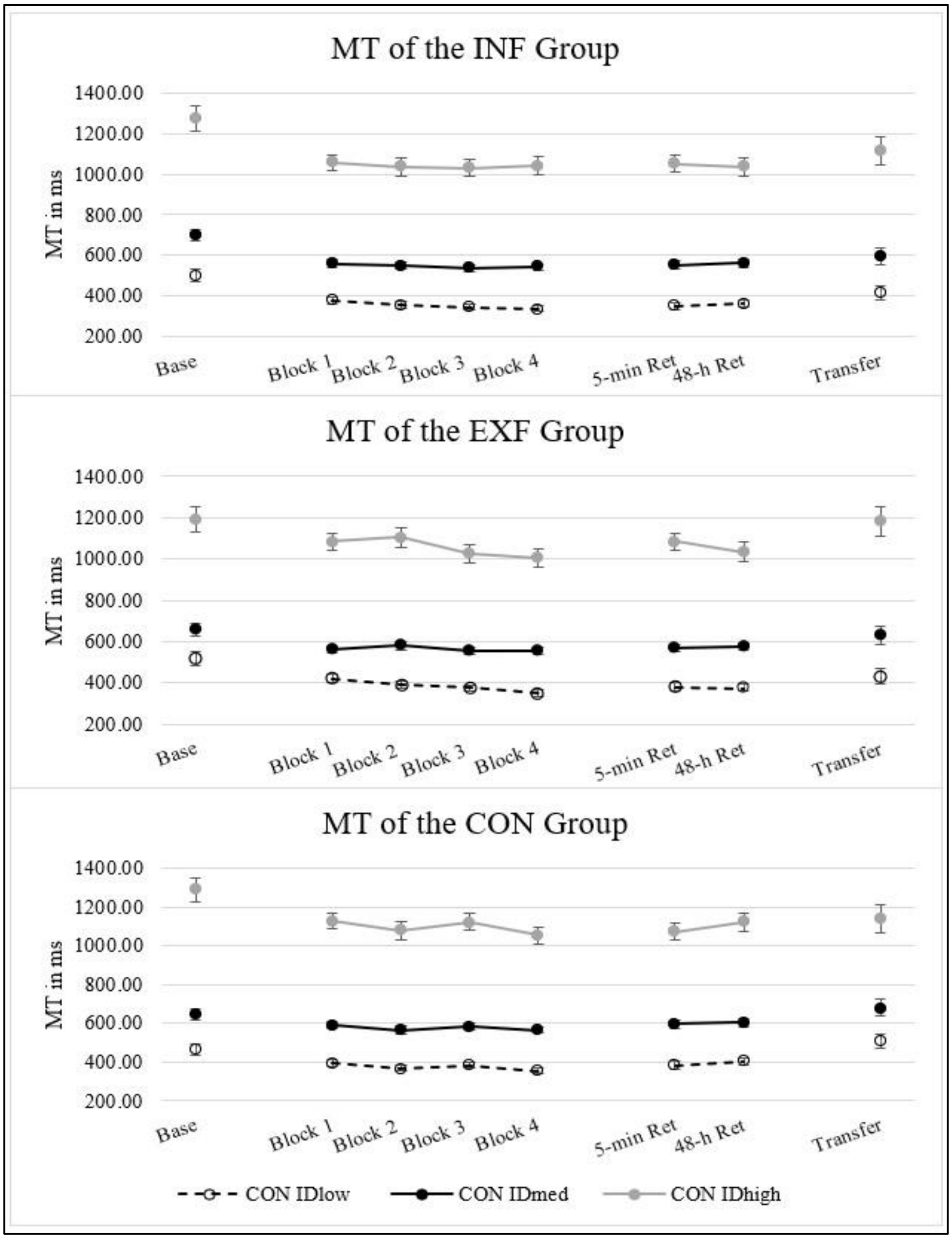


Figure 4.1. MT of ID Conditions by Group. Bars represents SEM of the within-factor. Base = Baseline, Ret = retention tests, Transfer = transfer test. Bars show SE. 3 separate tests were conducted 3 (Group) x 3 (ID) x 3 (base, 2 retention tests) ANOVA for the testing phase, 3 (Group) x 3 (ID) x 4 (Block) ANOVA for the acquisition phase, and 3 (Group) x 3 (ID) ANOVA for the transfer test. For practice, Block 2, 3, 4 were better than Block 1 ($p < .01$); for the testing phase, the two retention tests were better than Base ($p < .01$) and interaction of ID by time ($p < .01$). For all analyses, each ID was statistically different, and no group difference was found.

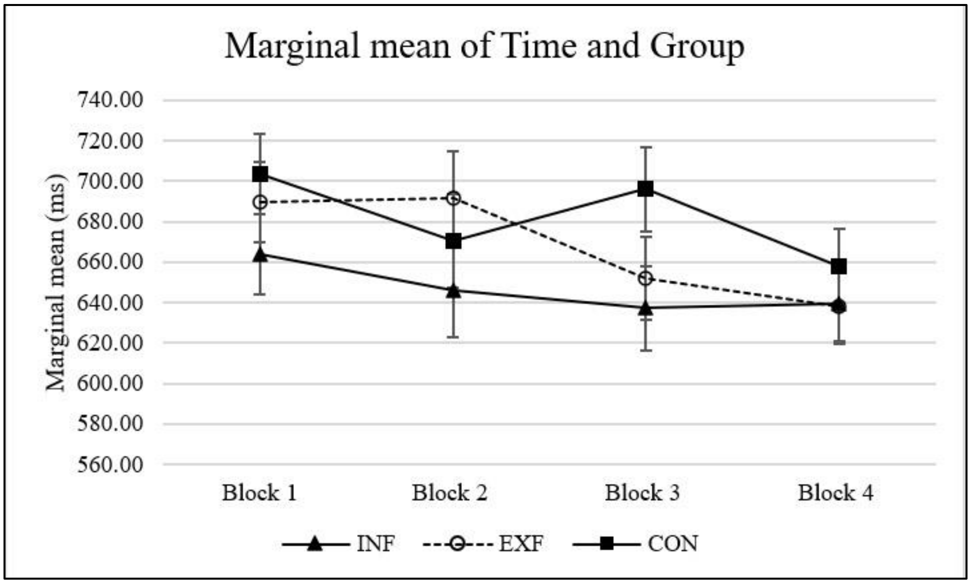


Figure 4.2. Marginal Mean of MT During the Acquisition Phase. Bars represents SEM of the within-factor. The mean scores are the marginal mean of ID conditions for each group.

Error taps

Figure 4.3. shows the number of error taps. There was a significant result in ID ($F_{1.24,70.75}$ = 386.74, p < .01, η^2_p = .87). *Post hoc* tests showed the error was greater in the ID_{low} than the ID_{med} and ID_{high} conditions (both p < .01), and the ID_{med} condition was greater than the ID_{high} condition (p < .01). No other difference was found to be significant.

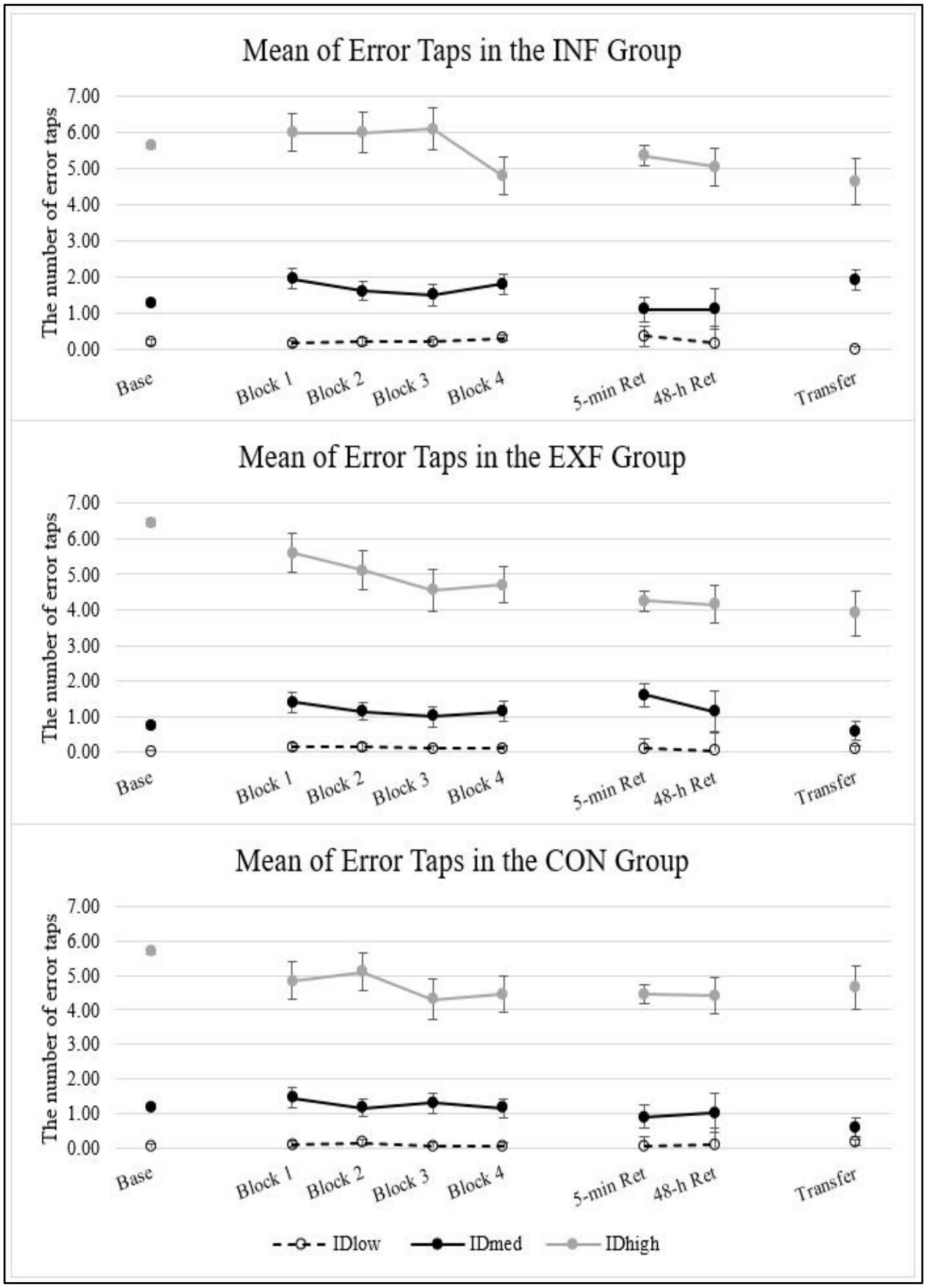


Figure 4.3. Mean of Error Taps. Bars represents SEM of the within-factor. Base = Baseline, Ret = retention tests, Transfer = transfer test. Bars show SE. 3 separate tests were conducted (Same as MT, See Figure 4.1.).

Testing Phase

Movement time

Mean and SD of scores of dependent variables are summarized in Table 4.1. Figure 4.1 shows performance changes between the baseline, retention tests, and transfer test. All the statistical results and effect size of the dependent variables are summarized in Appendix J. For the main analysis, there were main effects in ID ($F_{1.13,64.26}$ = 749.92, p < .01, η^2_p = .93), time ($F_{1.45, 82.80}$ = 54.99, p < .01, η^2_p = .50), and interaction of time by ID ($F_{1.65, 93.80}$ = 4.94, p < .01, η^2_p = .08). However, *post hoc* tests of the interaction effects showed the same statistical pattern: Examination of the ID factor showed that the ID_{low} at the baseline resulted in lower MT (*i.e.*, faster) compared to the ID_{med} (p < .01) and ID_{high} conditions (p < .01), where there was no difference between the the ID_{med} and ID_{high} conditions (p > .05). This pattern was the same for the ID_{med} and ID_{high} conditions in the 5-minute and 48-hour retention tests. Similarly (examining the time factor), in the ID_{low} condition, MT in the baseline was higher (*i.e.*, poorer performance) than the 5-minute retention (p < .01) and 48-hour retention tests (p < .01), where there was no difference between the 5-minute and 48-hour retention tests (p > .05). Again, this temporal pattern was statistically the same for the ID_{med} and ID_{high} conditions. We believe that the source of the interaction was the magnitude of improvements between the baseline and 5-minute retention tests for different ID conditions. For the ID_{low} condition, the mean difference (the degree of improvements) between the baseline and 5-minute retention test was 122.96ms, and it was 94.16ms for the ID_{med} condition. However, the mean difference in the ID_{high} condition was 183.22ms, indicating that the degree to which MT improved in the ID_{high} condition was greater than the ID_{low} and ID_{med} (non-statistically).

Table 4.1. Mean (SD) of MT during the Testing Phase

		Base	5-min Ret	48-h Ret	Transfer
INF	IDlow	500.16 (186.20)	346.78 (68.22)	360.32 (72.22)	412.95 (111.76)
	IDmed	699.74 (170.28)	552.05 (65.37)	560.59 (95.01)	591.79 (94.41)
	IDhigh	1276.33 (270.00)	1053.08 (125.02)	1035.50 (151.43)	1117.28 (240.17)
EXF	IDlow	517.78 (120.85)	381.17 (111.05)	378.90 (80.03)	434.39 (151.94)
	IDmed	656.70 (127.09)	569.43 (101.93)	575.10 (92.20)	629.84 (267.71)
	IDhigh	1192.81 (285.84)	1083.74 (262.58)	1034.93 (212.89)	1184.85 (190.30)
CON	IDlow	463.21 (86.73)	384.32 (77.80)	404.20 (85.77)	508.79 (294.58)
	IDmed	643.28 (87.73)	595.76 (86.51)	603.82 (78.20)	681.73 (414.38)
	IDhigh	1291.07 (288.95)	1073.73 (154.26)	1124.50 (260.13)	1140.11 (316.94)

Note. Base = Baseline, Ret = retention test, Transfer = transfer test. Mean (SD).

Dual Task Cost (DTC)

The results of the dual task procedure in the transfer test showed that there was a main effect in ID ($F_{1.73, 98.67} = 10.51$, $p < .01$, $\eta^2_p = .16$) with no difference between groups or interaction between ID and groups ($p > .05$ for both) (Figure 4.1).

The DTC represents the cost of a secondary performance about the primary task. Performance of the primary task may be affected by the performance of the secondary task. Thus, we analyzed the number of animal names (*i.e.*, the secondary task) between groups. The results of 3 (Group) x 3 (ID) ANOVA with repeated measures on the second factor showed that there was a significant difference in ID ($F_{2, 114} = 17.02$, $p < .01$, $\eta^2_p = .23$) with no difference between groups ($F_{2, 57} = .50$, $p > .05$, $\eta^2_p = .02$) or interaction ($F_{4, 114} = 1.85$, $p > .05$, $\eta^2_p = .06$). *Post hoc* tests on the ID factor revealed that the number of animal names were greater during the ID_{low} condition ($M_{marginal}$ = 4.12, SE = .25) than the ID_{med} (M = 2.67, SE = .20) and the ID_{high} (M = 2.92, SE = .16) conditions, $p < .01$, with no difference between the ID_{med} and ID_{high} conditions, $p > .05$. The mean and SD of the animal names in each group is shown in Table 4.2.

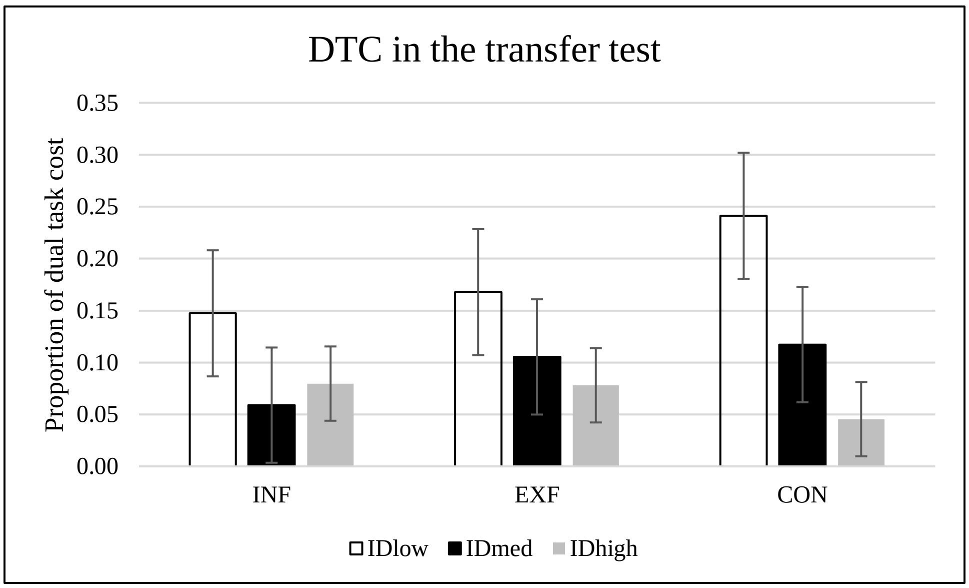


Figure 4.4. DTC in the Transfer Test. A higher value indicates a greater "cost" of a secondary task. The value zero indicates there is no influence of a secondary task. The value ranges from 0 to 1 (proportion). Bar represents SEM.

Table 4.2. Mean (SD) of the Number of Animal Names as a Secondary Task.

		The number of animal names
INF	IDlow	4 (1.67)
	IDmed	2.65 (1.27)
	IDhigh	3.35 (1.35)
EXF	ID low	4.3 (1.72)
	IDmed	3.2 (1.97)
	IDhigh	2.5 (1.00)
CON	ID low	4.05 (2.42)
	IDmed	2.15 (1.39)
	IDhigh	2.9 (1.25)

Note. The order of the condition was ID_{low}, ID_{med}, and ID_{high}, with “c”, “g”, and “p”, respectively.

Error taps

Table 4.3 shows the mean and SD. There were main effects in ID ($F_{1.41, 80.33}$ = 396.52, $p < .01$, $\eta^2_p = .87$), time ($F_{2, 114} = 5.2$, $p < .01$, $\eta^2_p = .08$), and interaction between ID and time ($F_{2.66, 151.76} = 7.00$, $p < .01$, $\eta^2_p = .11$). *Post hoc* tests with an ANOVA test in each ID showed that there was no difference across the time (baseline, 5-minute, and 48-hour retention tests) in the ID_{low} and ID_{med} conditions ($p > .05$), but there was a difference ($F_{1.95, 114.88} = 8.38$, $p < .01$, $\eta^2_p = .12$) in the ID_{high} condition. Pairwise comparison with Bonferroni correction of type I error showed that the number of error decreased from the baseline to 5-minute retention ($p < .01$) and to 48-hour retention tests ($p < .01$), whereas no difference was found between the two retention tests ($p > .05$).

In the transfer test, there was a significant difference in ID ($F_{1.33, 75.51} = 124.19$, $p < .01$, $\eta^2_p = .69$). *Post hoc* test on ID showed that the number of error taps were significantly lower in the ID_{low} than the ID_{med} ($p < .01$) and the ID_{high} ($p < .01$)

conditions. Although it did not reach significance, the group factor showed marginal difference with a medium effect size ($F_{2, 57} = 3.10$, $p = .053$, $\eta^2_p = .10$). Thus, we proceeded to conduct *post hoc* tests on the group factor. The results showed that the INF group tended to have a greater number of errors relative to the CON group ($p = .059$) with no difference between the EXF and CON, or EXF and INF groups (both $p > .05$).

Table 4.3. Mean (SD) of the Number of Error Taps during the Testing Phase.

		Base	5-min Ret	48-h Ret	Transfer
INF	IDlow	0.20 (0.52)	0.35 (0.67)	0.15 (0.49)	0.00 (0.00)
	IDmed	1.30 (0.91)	1.10 (1.17)	1.10 (1.17)	1.90 (1.69)
	IDhigh	5.65 (2.35)	5.35 (2.54)	5.05 (2.06)	5.40 (2.56)
EXF	ID low	0.00 (0.00)	0.10 (0.31)	0.05 (0.22)	0.10 (0.31)
	IDmed	0.75 (1.06)	1.60 (2.01)	1.15 (1.46)	0.60 (0.99)
	IDhigh	6.45 (2.26)	4.25 (2.71)	4.15 (2.46)	4.65 (2.87)
CON	ID low	0.05 (0.22)	0.05 (0.22)	0.10 (0.45)	0.15 (0.49)
	IDmed	1.20 (1.18)	0.90 (1.17)	1.00 (1.17)	0.60 (0.94)
	IDhigh	5.70 (1.90)	4.45 (2.33)	4.40 (2/56)	3.90 (2.85)

Discussion

The present study examined the effects of task difficulty when participants practiced a Fitts' reciprocal tapping task with an attentional focus cue. Additionally, the present study also examined whether an EXF is superior to and an INF is inferior to a non-attentional focus strategy ("*do your best*" or CON). It was hypothesized that the CON group would perform better in the easy condition relative to both EXF and INF groups due to an automatic process when individuals performing an easy task; The EXF group would perform better in the moderately difficult condition where individuals require conscious control but the information to be processed is not overwhelming; The INF group would perform worse than the EXF group due to disruption of efficient information process (*i.e.*, hypothesis regarding task difficulty interaction). Further, for the direction of attentional focus effects, it was hypothesized that the EXF group would perform better relative to the INF and CON groups and the INF group would perform poorly compared to the EXF and CON groups. Lastly, the degree of automaticity was measured using dual task procedure by taxing working memory (Abertney, 1999), and it was hypothesized that the EXF benefits would be emphasized, and thus the EXF group would perform better than the CON and INF groups during the transfer test.

Results showed that the learning effects for the performance outcomes, exhibited a clear difference in performance between ID’s. Further, participants improved the task following practice. These results suggest that the manipulation of task difficulty was successful and there were learning effects. The improvements in MT implies an improved information processing capacity (Fitts, 1954; Fitts & Peterson, 1964) and cognitive process became more efficient by experience/familiarity (Shiffrin & Schneider, 1976; Schneider & Shiffrin, 1977).

Regarding the degree of influence of task difficulty and practice on attentional focus, the results of MT in the retention and transfer tests showed no difference between the EXF, INF and CON groups in all difficulty conditions and did not differ in the degree of automaticity, measured as DTC. This suggests that the learning effect and the efficiency of the information process did not differ by attentional focus manipulation. By examining the results of MT, the hypothesis regarding task difficulty was not supported. However, Fitts' Law task has a tradeoff relationship between the speed of the movement and accuracy. Thus, the number of error taps were assessed. The results showed that there was no difference in the retention tests between groups; however, in the transfer test, there was a trending effect (p = .053) with a medium effect size (η^2_p = .10) in group. Specifically, the INF group resulted in a greater error relative to the CON group, where no difference was found between the INF and EXF, and the EXF and CON. Collectively, results from the present study did not support the hypothesis regarding task difficulty influence on attentional focus and did not support the bidirectional effects of attentional focus when examining MT. However, a trend of attentional focus effects emerged in error during a dual task transfer test when the degree of automaticity is tested.

First, regarding the difference in the results of MT and accuracy, attentional focus may be more susceptible to a fine motor control. Research using an accuracy task has consistently shown that an INF was inferior to an EXF in dart throwing (Lohse et al., 2010; Marchant et al., 2009), Fitts' reciprocal tapping task (Raisbeck et al., 2020), basketball shooting (Zachry et al., 2005), and piano key pressing task (Duke, Cash, & Allen, 2011), whereas some studies that adopted a gross motor skill have reported no difference between an EXF and INF (de Melker worms et al., 2017; Lawrence et al., 2011; Winkelman et al., 2017 in Exp. 2). It is possible that more complex movements have greater sources of variabilities, which may affect performance outcomes. Another potential explanation is that a more complex movement may require probing attentional focus to multiple cues. A general experimental setting in the attentional focus paradigm uses a single cue. As a result, a single instructional cue may not sensitively affect performance outcomes in a more complex movement. This rationale indicates that the difference should be expected in the present study. However, in a reciprocal tapping task of the present study, participants were required to perform each trial under a certain amount of error within a predetermined number of trials. Even though the goal of the task was to move as fast as possible, it must be performed under the premise of relatively accurate performance. Therefore, it is possible that participants may have directed their attention to an assigned instruction only around the moment of hits on the targets rather than paying attention to internally or externally throughout the entire trial while moving the stylus between targets. This leaves the possibility that the attentional focus effects may be minimal in MT.

Another important finding of the present study was that the attentional focus effect (although non-significant) was trending to be evidential only in the transfer test when participants' working memory was presumably loaded by a secondary task. This result replicated the findings by Poolton et al. (2006) in golf putting in that there was no difference during practice nor retention tests but the disruption of performance by an INF was evident in the dual task transfer test. Although research has shown attentional focus affects both performance (Ducharme et al., 2015; Porter et al., 2010; 2012; Wulf & Dufek, 2010) and the learning effect (Bahmani, Diekfuss, & Kharestani, 2018; Christina & Alpenphal, 2014; Lohse, 2012), some studies showed that the EXF benefit emerge only after days of practice (Wulf et al., 1998; McNevin et al., 2003). For example, Wulf et al. (1998) conducted a ski-slalom simulation task (Exp.1) and balance task (Exp.2), and the former task exhibited the EXF benefits in both performance and retention, but the latter task showed the EXF benefits only in the retention test. Wulf et al. explained that novices are required to figure out how to move the ski-slalom platform, engaging in more cognitive processes. Consequently, attentional focus was effective immediately. Contrary, participants were able to perform the balance task prior to the experiment. In the former task, the initial goal was to consciously control their attention to the task to become able to perform the task, whereas the goal of the task in the latter was to *improve* the task that had already been established. As a result, cognitive interventions became effective after a certain skill level is reached (Wulf et al., 1998). Similar to the balance task in Wulf et al. (1998), participants in the present study were able to perform the task, regardless of the quality of performance before the experiment had proceeded. Since the information process may have been, to some degree, already efficient in the beginning, even if there was a disruptive process by an INF, it is possible that attentional capacity had enough room to compensate for the inefficient process evoked by an INF. However, when working memory was loaded by a secondary task, the disruptive process by an INF may have become harmful due to limited capacity of working memory. The present study hypothesized that the benefits of an EXF would be emphasized under the circumstance of loaded working memory. However, this hypothesis was not supported. Rather than the effect of an EXF, the present study showed that an INF more affected the performance outcome. Although the present study does not have the evidence to support the proposition by Poolton et al. (2006) that an INF adds loads to working memory, the performance results implied that an INF was detrimental when working memory was theoretically challenged. In the future, studies using neurophysiological measurement tools may develop the understanding of this proposition.

The results specific to the task difficulty effect did not show differences between attentional focus groups. Proponents of task difficulty effects explain that when the task requires minimal voluntary correction of movements, attentional focus intervention may not be effective (Wulf et al., 2007), presumably requiring little cognitive process. Previous studies showed that task difficulty (Becker & Smith, 2013; Landers et al., 2005; Wulf et al., 2007) and/or skill level (Porter & Sims, 2013; Winkelman et al., 2017; Wulf, 2008) affects the attentional focus relationship, while others showed the EXF benefits regardless of task difficulty (Alorani et al., 2019; Raisbeck et al., 2020) or skill level (Asadi et al., 2019; Halperin et al., 2017; Wulf et al., 2002). One explanation for the inconsistent results of the present study may be attributed to the study design. Previous studies adopted a within-subject design without a control group (Alorani et al., 2019; Landers et al., 2005; Raisbeck et al., 2020; Wulf et al., 2007), whereas the present study was a between-subject design with three groups. Accordingly, the previous studies had a greater statistical power, and individual differences were statistically considered. Recently, individual difference has been found to play an important role for the attentional focus effects (Bahmani, Diekfuss, & Kharestani, 2018; Sakurada, Hirai, & Watanabe, 2016). Additionally, a challenge exists when investigating task difficulty with a between-subject design. Task difficulty has, at least, two dimensions: Absolute (nominal) and relative (functional) (Gaudagnoli & Lee, 2004; Logan, 1985). In the present study, ID corresponds to nominal difficulty since ID of 2 is easier than ID of 4 regardless of individuals. However, individuals' performance at ID of 4 can vary by various inherent and acquired factors. As a result, an ID of 6 may be difficult for some individuals but not for others. In the present study, non-dominant hand was used to consider the skill level, however, healthy young individuals have performed similar reaching and aiming tasks for numerous times daily. As a result, task difficulty may not have been difficult enough for the present sample. Future studies should be directed to consider functional difficulty (*e.g.*, assigning groups based on the baseline performance).

Although the study design adopted in the present study limited the ability to control individual difference, it is important to note that there is no consensus to define 'task difficulty'. A task, in the nominal difficulty term, becomes more challenging for a motor skill that requires more musculature, degrees of freedom, cognitive process, or complexity of movements. Accordingly, the level of difficulty chosen for a study is arbitrary. Although participants may have been relatively efficient regarding the type of movements (reaching and hitting targets), which is one of the limitations of the present study, the present study objectively manipulated difficulty by the bits of information required to carry out the task (Fitts, 1954; Peterson & Fitts, 1964). Therefore, increasing MT indicates an increase in the processing efficiency. Given that attentional focus affects Fitts' Law task performance (Aloraini et al., 2019; Raisbeck et al., 2020), future studies should be directed to investigate the factors that affect processing efficiency and how many bits of information is required to see attentional focus effects or how much information processing an EXF increases efficiency or an INF decreases efficiency.

One of the primary questions examined in the present study was the directionality of attentional focus effects. Most of the previous studies in the attentional focus paradigm have been conducted with a dichotomous comparison between EXF and INF (Alorani et al., 2019; Lohse et al., 2010; Marchant et al., 2009, 2013; Raisbeck et al., 2020; Wulf et al., 1998, 1999, 2001; Zachry et al., 2005). Comparison between two strategies poses a challenge in the interpretation of the data because if one strategy is used as a reference, it is unknown whether the direction of the effect is unidirectional (*i.e.*, an EXF is superior to an INF or an INF is inferior to an EXF) or bidirectional (*i.e.*, an EXF is superior *and* an INF is inferior). Therefore, the comparison should be made by instructional strategies relative to a no instructional strategy. In the present study, an EXF effect was not evident, but an INF detrimental effect over a non-strategy (*i.e.*, CON) was present during the transfer test. This result further supported the proposition by Poolton et al. (2006) that attentional focus effect is rather by a disruption of an INF than automaticity promoted by an EXF. However, a considerable amount of literature has shown different results. While a few studies supported the bidirectional effects (*i.e.*, EXF is superior to CON and INF is inferior to CON) (Becker, Fairbrother, & Couvillion, 2018; Halperin et al., 2015; Makaruk et al., 2013), some studies showed an EXF was superior to both INF and CON conditions (Abdollahipour et al., 2015; Marchant et al., 2011; Porter & Anton, 2011; Wulf & Su, 2007; Wulf et al., 2009), and others showed an EXF was not different from a CON and an INF was inferior to both EXF and INF (Duke et al., 2011; Marchant et al., 2007; Halperin et al., 2017). Considering relatively consistent results between EXF and INF (Wulf, 2013) with no consistent patterns against a CON condition, one explanation is that some motor skills naturally have affinity to internal or external thoughts. Participants in a CON group are free to vary their attentional foci, think nothing, or simply think to do their best. As a result, participants in the CON group may think more externally when salient EXF/INF cues are naturally present in the motor skill. For example, walking requires no object manipulation, but playing basketball has more task relevant EXF cues (*e.g.*, the basket, balls, defensive players). Maxwell and Masters (2002) proposed that an INF would invoke additional explicit knowledge. For example, when performing golf, EXF cues are salient in the environment (*e.g.*, trajectory of the ball). Consequently, an EXF instruction functions as an attentional direction without providing new information. Contrary, providing an INF cue in this situation (*e.g.*, arm motion, trunk rotation) is adding information to the performers' working memory with already existing environmental cues. This implies that, first, an INF may not be as detrimental when motor skills have salient INF cues (*e.g.*, walking) and EXF cues are not salient. Second, an EXF may be effective when the instruction makes EXF cues more salient or avoids performers from internally focused attention, and thus EXF becomes meaningful rather than redundant. For example, placing a cone or marker during long jump (Porter et al., 2012) or shotput (Makaruk et al., 2013) may have increased salience of EXF cues. As a result, an EXF may have functioned as supplementary, resulting in superior performance to a CON condition in Makaruk et al. (2013). Contrary, the EXF cue in the present study may be redundant to the goal of the task since participants may have already focused on the stylus. Thus, an EXF cue may not have been supplementary. Additionally, the primary joint that is used in a reciprocal tapping task is the shoulder joint, and the task is executed primarily by moving the participant's arm. Thus, it is also possible that an INF cue in this study was not meaningful. Previous research by Raisbeck et al. (2020) used "focus on moving your arm" in a reciprocal tapping task and found the EXF benefits. In the present study, we purposefully used the "hand" instruction for the INF group to eliminate the potential effect of physical distance between EXF and INF cues. However, this manipulation may have influenced the relevance of instruction. More studies are warranted for the prediction of the relationship between EXF, INF, and CON, however, the results of the present study suggest that an INF disruptive effect is greater than an EXF beneficial effect.

Although it was not our primary theoretical question, our results also provided an important support regarding optimal task difficulty and motor learning. The results showed the main effect in interaction of time and ID in both MT and the number of error taps indicate a differential learning magnitude. The magnitude of improvement was largest in the ID_{high} condition. Especially for accuracy, the number of error taps did not change following two days of practice in the easier conditions. Considering the improvement of MT, participants still improved the overall task since moving faster with no significant change of errors indicates more efficient movements. Traditionally, the error limit of a Fitts' Law task is restricted to 5 – 10% (Elliot & Khan, 2010 for review), and errors exceeding these ranges are discarded (Wu, Yang, & Honda, 2010). Since the purpose of these studies is mathematical prediction of lawful behavior, this method minimizes the speed-and-accuracy tradeoff. However, the error limit in the present study was set relatively broader since the purpose was to understand the learning effects in both accuracy and speed (*e.g.*, Snoddy, 1953). Our results partially supported previous findings that the magnitude of motor learning is dependent upon task difficulty (Gaudagnoli & Lee, 2004). The optimal challenge point theory proposes that the optimal point of practice is where the task is not too easy or difficult. If the task is too easy, there is little information to extract, whereas if the task is too difficult, it causes information overload (Gaudagnoli & Lee, 2004). In the present study, the greatest improvements did not occur in the moderate difficulty. However, we do not believe the present results deny the optimal challenge point framework. It is clear (Figure 4.1 and 4.3) that the difference between the ID_{low} and ID_{med} was closer relative to the difference between the ID_{high} and ID_{low} and ID_{high} and ID_{med} conditions. Although ID's used in the present study were evenly distributed (*i.e.*, ID = 2, 4, and 6, respectively), the ID_{high} condition used in the present study may not be difficult enough and both ID_{low} and ID_{med} conditions may be easy. Although the optimal level of difficulty for motor learning is beyond the scope of the present study, our results supported previous findings that the rate of learning depends on the task difficulty (Akizuki & Ohashi, 2015; Joseph, King, & Newell, 2013).

Lastly, it is important to note that the results of the transfer test phase showed a clear order effect. The cost of the secondary task (DTC) was higher in the easier conditions than the more difficult condition. All participants performed from the easy, medium, and to difficult condition. Thus, the order affected the results. However, it is also possible that the movement speed affected the results. During the most difficult condition, participants' movements were well below their maximal physiological capacity due to the accuracy criteria. Thus, there may have been a less effect of a secondary task in MT for the difficult condition. However, during the easy condition, participants were moving faster due to a large tolerance limit. Consequently, there would be a less requirement for accuracy and participants may have been moving the stylus near the maximal capacity. Thus, the decline in MT by a secondary task may be more sensitive in the easier conditions.

Conclusion

In the present study, participants practiced a Fitts' reciprocal tapping task that varies in three different task difficulties for two days. The results showed that participants improved MT while reducing the number of error taps. The magnitude of the improvement was more evident in the most difficult condition. There was no differential effect of instructional strategies between EXF, INF, and CON during practice, 5-minute and 48-hour retention tests in any difficult condition. However, a trending effect with a medium effect size indicated a disruptive effect by an INF in the transfer task when theoretical working memory was loaded by a secondary task. However, in contrast to our hypothesis, the EXF benefits were not evident when working memory was loaded. These results supported the proposition by Poolton et al. (2006) of the information process perspective in that an INF is detrimental due to an increased load to working memory rather than an EXF promoting an automatic process. Regarding the directionality of the attentional focus effects, although more investigation is required since the attentional focus in the CON group may have been more prone to the EXF or an EXF cue may have been redundant, the data suggest that the attentional focus effects was unidirectional of an INF effect, not bidirectional effects.

CHAPTER V

MOVEMENT AND TIME SERIES VARIABILITY AND ATTENTIONAL FOCUS: THE EXPLORATORY ANALYSIS OF THE TIME SERIES DATA OF THE JOINT ANGULAR VELOCITY

Abstract

Attention to the effects of the movement (external focus, EXF) has been demonstrated to be an effective motor learning strategy relative to attention to body movement (internal focus, INF). Although some evidence shows that an INF induces disruptive neuromuscular coordination, the mechanism of attentional focus is still unclear. This may be due to the lack of knowledge regarding how attentional focus affects the control of movement variability or the temporal structure of variability (*i.e.*, time-series variability). Therefore, the present study examined movement variability as SD and coefficient of variance (CV) and time series variability as Sample Entropy (SampEn) of the joint angular velocity, while the EXF (n = 20), INF (n = 20), and CON (n = 20) groups practiced Fitts' reciprocal tapping task. Participants practiced moving a stylus reciprocally between two targets during a 30s trial with three different levels (Index of Difficulty = 2, 4, and 6). The shoulder, elbow, and wrist joint angular velocity were captured with a 3D motion capture system at 100Hz in the baseline, 5-minute

retention test (following two days of practice), 48-hour retention test, and dual task transfer test. The results showed that the mean joint angular velocity increased with practice, while the shoulder joint exhibited the greatest velocity. For SD, variability increased with practice, and the proximal joint variability was higher than the distal joint. Contrary, CV and SampEn reduced with practice and the distal joint variability was higher than the proximal joint. Further, although no group difference was evident, CV showed a marginal effect, suggesting that the INF group had a lower CV than the CON group in the transfer test. The results are discussed based on the role of joint motor control, the interpretation of the metrics of variability, and attentional focus and variability.

Introduction

A large body of literature has shown that directing an individual's attention to the effects of the movement on the environment (external focus, EXF) is more effective in motor learning and performance compared to directing attention to body movements (internal focus, INF) (Wulf, 2013 for a review). This beneficial effect of an EXF has been demonstrated in various motor skills, including jumping (Ducharme et al., 2015; Wulf & Dufek, 2010), dart throwing (Lohse et al., 2010; 2013; Marchant et al., 2009), basketball free-throw (Zachry et al., 2004), balancing (McNevin et al., 2003; Wulf et al., 1998; 2001), golf (Christina & Alpenfals, 2014), and discrete (Alorani et al., 2019) and paced aiming task (*i.e.*, Fitts' Law task) (Raisbeck et al., 2020). The effect of attentional focus on motor control and learning is explained by the constrained action hypothesis (CAH) (McNevin et al., 2003; Wulf et al., 2001), proposing that an EXF promotes more automatic process by naturally self-organizing the motor system, which leads to a greater performance. Contrary, an INF interferes with the motor system that results in degraded performance by evoking inefficient neuromuscular coordination in accuracy and strength tasks (*e.g.*, Lohse, 2012; Lohse et al., 2010; Marchant & Greig, 2009; Marchant et al., 2011) or reduced subtle postural adjustments during balancing (McNevin et at l., 2003; Wulf et al., 2001). However, the exact underlying mechanism of the self-organizing function by an EXF or motor system disruption by an INF is still unclear.

To develop the understanding of the attentional focus effects, researchers have suggested applying a larger theoretical framework of motor skill acquisition, rather than a hypothesis specific to attentional focus (Oudejan et al., 2007). One of the predominant theories in motor learning is a theory related to variability. Traditionally, variability implied variability of performance. Performance variability has been considered as a random noise (*i.e.*, Gaussian noise) because of the imperfect nature of the human systems (Davids et al., 2003), and thus largely ignored (Slifkin & Newell, 1998;1999). However, different forms of variability may provide meaningful information that explain various behaviors such as motor control, motor learning, and physiological changes (Brach et al., 2005; Chiu & Chou, 2013; Kelso, 1995; Lipsitz & Goldberger, 1992). Bernstein (1967) proposed that variability of *movements* (*e.g.*, joint angular displacement, angular velocity) increases with learning, which results in the decrease of performance variability. Empirical evidence has demonstrated that movement variability of the joint angular displacement as SD gradually increased as participants practiced a ski-slalom task (Verejiken et al., 1992). Increasing movement variability is indicative of exploiting available degrees of freedom, which makes the performer more adaptable and adjustable to various constraints (Newell, 1986). Another perspective of variability is *time series* variability, which proposed that a temporal structure of trial-to-trial fluctuations of performance possesses meaningful information (Brach et al., 2005; Newell & Vaillancourt, 2001; Stergiou & Decker, 2010; Thelen & Ulrich, 1991). For example, when walking, the length of each step varies slightly. If the variability of step lengths is calculated with SD of the mean step lengths, it loses the temporal structure of variability. Research examining trial-to-trial fluctuation patterns (*i.e.*, time series variability) has revealed that the patterns that are too predictable/rigid (*e.g.*, similar step lengths) or too random were related to poor performance, fall risks in older adults, and pathology (Brach et al., 2005; Hausdorff, Rios, & Edelberg, 2001;Vaillancourt & Newell, 2002). Accordingly, fluctuation patterns that are, to some extent, random but possesses repeated patterns (*i.e.*, stochastic process) is considered as being complex, flexible, and adaptable to changes in the systems and/or environment, and therefore the optimal motor control system (Stergiou & Decker, 2010). Time series variability is also sensitive to cognitive processes. Research has shown that gait pattern with a cognitive task (drawing attention away from the motor task) compared to normal walking changed time series variability of gait (Potvin-Descrochers et al., 2017). This suggests that an underlying mechanism of cognition (*e.g.*, attentional focus) can be studied by examining variability of motor behavior (Van Orden, Holden, & Turvey, 2005).

To this end, researchers have applied theories of variability to understand the attentional focus mechanism. Lohse et al. (2014) showed in a dart throwing task that the shoulder and elbow joint angles and angular velocity were larger for the EXF condition relative to the INF condition, and this increase in the movement variability decreased performance variability and was related to the improved coordination between the shoulder and elbow joints. Rhea et al. (2019) examined time series variability of the center of pressure displacement during a postural control, using a mathematical tool called Sample Entropy (SampEn), and showed that the EXF condition led to a greater complexity of time series variability, which indicates that an EXF led to greater regularity (Kal et al., 2013) or self-organized motor control (Rhea & Kiefer, 2014). These findings are replicated in motor skills that are less goal oriented, such as hopping in a place (Fietzer et al., 2018) and a paced leg movement (Kal et al., 2013). Therefore, an underlying mechanism of attentional focus effects may be due to the changes in the magnitude of variability (*i.e.,* movement variability) (Fietzer et al., 2018; Lohse et al., 2014) and structure of variability (*i.e.*, times series variability) (Kal et al., 2013; Rhea et al., 2019).

Although the relationship between the EXF/INF and variability is still rudimentary, others did not find the attentional focus effects on movement variability (Vidal et al., 2018) or time series variability (Diekfuss et al., 2018). While these differences may be due to the nature of the task, study design, and other methodological differences, it is critical to determine whether variability is an underlying mechanism of motor control related to attentional focus. In the present study, participants practiced a Fitts' reciprocal tapping task with three task difficulties. From previous findings that the EXF increased complexity of time series variability (Kal et al., 2013; Rhea et al., 2019) and movement variability (Lohse et al., 2014), therefore it was hypothesized that the EXF group would have a higher variability relative to the INF group. Further, since movement variability has been shown to increase with performance improvement (Verejiken et al., 1992), it was hypothesized that the variability would increase in the retention tests compared to the baseline. Lastly, due to the increased difficulty that requires greater adjustments, variability would be higher in the more difficult conditions relative to the easier conditions. Regarding joints, it was hypothesized that variability of the distal joint (*i.e.*, shoulder) would be greater for a more adaptable motor control while the proximal joint (*i.e.*, wrist) would show more fixed variability to produce consistent performance.

Methods

Participants

Sixty-five healthy young adults volunteered for the present study. A total of sixty healthy young adults between the ages of 18 to 50 years (*M* = 22.21yrs., *SD* = .67 for males, *M* = 23.46 yrs., *SD* = .81 for females) completed the study. Participants were naive to the task free of upper extremity injuries, surgery, or pain at least in the last six months. Hand dominance was determined with the Edinburgh Handedness Inventory-Short Form (Veale, 2014), and two participants in the INF group, one participant in the EXF group, and three participants in the CON group were determined as left-handed. The other 54 participants were right-handed. No participants were determined as a mixed handed. The institutional review board approved the study and participants completed an informed consent prior to participation.

Task and Apparatus

The task was a modified reciprocal Fitts' task (*e.g.*, Fitts, 1954; Raisbeck et al., 2019; Salmoni & Mcilwain, 1979; Sasangohar, MacKenzie, & Scott, 2009), which was adapted in the previous attentional focus studies (Alorani et al., 2019; Raisbeck et al., 2019). The task was performed on a table (69.85 x 76.45 cm), and required participants to tap back and forth between two horizontally aligned targets with a stylus (2 x 2 x 9 cm, width x length x height, respectively) during a 30-second trial (Figure 3.2). Two movable platforms were stabilized on a 40 cm rail. Targets (7 x 7 cm) vary in the proportion of the *hit area*, with the center marked with a crosshair (1x1cm) and *mishit area* (Figure 3.2). Knowledge of results specific to error hits was provided with an LED light that turned on when the stylus touched the mishit area. Task difficulty was calculated using the Index of Difficulty (ID), where ID = $\log_2$ (2D/W) (Fitts, 1954; Fitts & Peterson, 1964). D represents the distance and W represents the size (*i.e.*, width) of the targets. For the present study, W was calculated by the tolerance limit (*i.e.*, the remaining width after subtracting the width of the stylus). For example, for the width of the stylus is 2 cm and target area width of 6cm, ID was calculated as $\log_2$ (2D/4 cm). For the difficulty manipulation, the present study used three different hit areas (3 x 3, 4 x 4, and 6 x 6 cm) and three distances (8cm, 16cm, and 32cm, the center of one target to the center of the other target). The easiest condition was ID of 2 (ID_{low}), medium difficulty was 4 (ID_{med}), and the highest difficulty was 6 (ID_{high}).

To measure performance (the number of hits), reflective markers were attached to the stylus and tracked by a 3D motion capture system (Qualisys, Sweden). The data were collected at 100Hz sampling frequency. Auditory signals were introduced for three time points as a ready, start, end signal. The ready signal was presented (50ms duration). After 500ms, the start signal (50 duration) was presented. Each trial was 30 second, thus the end signal was presented after 3000ms from the start signal. All data was processed with MATLAB software (Mathworks, MA).

Procedure

The overview of the study design is summarized in Figure 3.2. At the beginning of the experiment, participants completed the Handedness questionnaire (Veale, 2014). Reflective markers are placed on participants' non-dominant hands of the upper limb joints. A shoulder marker was placed on the acromion process, elbow marker was placed on the lateral epicondyle of the humerus, wrist marker was placed on the radial styloid process, and finger marker was placed on the head of the metacarpo-phalangeal joint. The bony landmarks were identified by palpation by the investigator. Following the marker placement, participants were asked to sit in a chair in front of a table and as close to the edge of the table to minimize the trunk motion. Participants were also informed to maintain the position during the experiment. Then, participants were informed of general procedure. Explanation of general procedure included: holding the top part of a stylus from the side with three fingers (thumb, index, and middle fingers); the task was to move a stylus back and forth between two targets; and the goal of the task is to tap the targets as many times as possible during a 30 second trial, but emphasizing accuracy. Participants were told to aim at the center of the target. The latter method was used for the present study. The maximum number of errors (*i.e.*, error limit) that participants can make was predetermined and used movement time (MT) (the number of taps divided by 30s) as a primary dependent variable. For each trial, participants were asked to 1) wait for the start signal while holding the stylus on the right target, 2) begin the reciprocal movements only after the start signal, 3) hit the targets with the stylus as perpendicular to the targets as possible, 4) continue to reciprocally move the stylus back and forth even if they made an error or missed tapping the target, and 5) perform additional trials if they made more errors than an error limit.

Prior to the baseline, participants received two 30-second trials with their dominant hand with ID of 3. During this phase, the emphasis was placed on understanding the general procedures. *A priori*, one additional trial was determined to provide if participants did not understand the procedure. None of the participants did not perform a third familiarization trial.

Following the familiarization phase, participants performed one 30-second baseline trial for three difficulties: ID_{low}, ID_{med}, and ID_{high} in the order of the low ID to high ID conditions. The error limits for each ID were 2, 4, and 10 error taps for ID_{low}, ID_{med}, and ID_{high}, respectively. These error limits were predetermined from a pilot study (N = 11). Participants were reminded of the goal of the task and performed the trials with their *non-dominant hand*. The investigator counted the number of errors and reported to participants every after trial. A trial was recollected when participants made any movements prior to a start signal or exceeded the error limits. To maintain the number of trials relatively similar across participants, the maximum number of trials for each ID during the baseline was predetermined as three trials. If participants did not complete a trial below the error limit within three trials, that participant was excluded. None of the participants exceeded this predetermined limit of trials.

Following the baseline, participants were randomly assigned to one of the EXF (n = 20), INF (n = 20), or control (CON, n = 20) groups. The goal of the task was reminded, and participants were informed of the importance of complying with the instructions that they would receive. Participants in the EXF group were told, "*mentally focus on moving the pen as fast and accurately as possible*". The instruction for the INF group was, "*mentally focus on moving your hand as fast and accurately as possible*", and the instruction for the CON group was, "*mentally focus only on doing your best"*. The instruction was provided in a piece of paper to distinguish it from other general procedures provided during the familiarization phase and repeated prior to every trial. The acquisition phase consisted of four blocks of nine trials of three consecutive trials of ID_{low}, three trials of ID_{med}, and three trials of ID_{high}. On Day 1, participants performed two blocks, with the order from the low to high ID conditions in Block 1, but the order of difficulty was randomized for Block 2. On Day 2 (48 hours later), participants revisited the lab and completed two additional blocks (a total of 18 trials) with the randomized order of ID conditions. Throughout the experiment, the same error limits (2, 4, and 10 for ID_{low}, ID_{med}, and $ID_{high,}$ respectively) were used.

For each ID, participants completed at least two trials below the error limit. That is, if participants did not exceed the error limit across three trials or exceeded one trial out of three trials, no additional trial was completed. However, if two trials exceeded the error limit within the first three trials, additional trials were collected until the second trial below the error limit was collected. The maximum number of total trials for each ID in each block were determined *a priori* as five trials to maintain the number of practice trials relatively similar across participants. If participants were not able to complete at least two trials below the error limit by the fifth trial, that participants were excluded. None of the participants exceeded five trials.

Following the acquisition phase, participants completed a 5-minute delayed retention test with the same assigned instructions during the acquisition phase. On Day 3, participants completed a 48-hour retention test with the same procedure of the 5-minute retention test. Following the 48-hour retention, participants completed a dual task transfer test. Participants were asked to perform the task while naming as many animals as possible starting with a given alphabet letter. Participants performed one trial low, medium, and high ID condition with C, P, and G, respectively. The questionnaire procedure was also the same as the baseline and retention tests. All participants completed the experiment on either Monday/Wednesday/Friday or Tuesday/Thursday/Saturday schedule.

Data Analysis

Data before and after the start and end signals was eliminated, missing data were interpolated with spline interpolation function of MATLAB, and these data were filtered using a Savitzky-Golay (SG) filter ($r = 1$, $m = 9$). The parameters were determined from pilot data by qualitatively examining the residual plot, assessing normality, and superimposing the raw data over the filtered data. The position of the targets was determined from 5s static trials. The spatial accuracy of measurement was also determined by a 5s static trial, and this was 0.02 mm SD in the x, y, and z axis from one of the markers. In the present study, the y axis represents the horizontal movements and the z axis represents the vertical movements.

The coefficient of variation (CV) was calculated as SD/Mean x 100 (Brach et al., 2005). The shoulder joint was determined from the right shoulder marker, left shoulder marker (the axis of rotation), and elbow marker; the elbow joint was determined from the left shoulder marker, elbow marker (the axis of rotation), and the wrist marker; the wrist joint was determined from the elbow marker, wrist marker (the axis of rotation), and the finger marker. For the left-handed individuals (performing the task with their right hand), the shoulder joint was determined from the right shoulder marker, left shoulder marker (the axis of rotation), and elbow marker. The joint angle was determined by identifying three-dimensional coordinates of each marker (*i.e.*, identifying the resultant vectors in the three-dimensional space and determining the angle between the vectors) (Figure 5.1). The derivative of the obtained angle displacement data for each joint was measured for angular velocity. This angular velocity was used for sample entropy (SampEn) measures. SampEn (m,r,N) is "*the negative natural logarithm of the CP (conditional probability) that a dataset of length N, having repeated itself within a tolerance r for m points, will also repeat itself for m+1 points, without allowing self-matches* (pp.789)" (Lake, Richman, Griffin, & Morman, 2002). A larger SampEn output indicates a more complex but too large output indicates a random irregular signal (*i.e.*, no match), whereas a lower output indicates a regular signal pattern with SampEn = 0 indicates a sine wave with no noise. Since the output of SamEn is sensitive to the parameters (Yentes, Hunt, Schmid, Kaipust, & McGrath, 2013), the parameters m and r were determined by randomly sampling ten participants' data and qualitatively examining the optimal parameters, using the previous recommendation (Lake et al., 2002). For the present study, $m = 2$ and $r = .1$ were adopted for all the difficulty conditions and joints. For SD and CV of the joint angular velocity, the absolute value of the joint angular velocity was obtained since the negative and positive displacement may cancel out with each other.

For performance, the instant of taps was determined in the following manner. First, a top right reflective marker on the stylus in the z axis was identified. Then, the ranges approximately the bottom of the marker of each stroke were identified. Finally, the lowest point within each range was determined as the instant of hit. Performance was measured in three different ways: The primary performance measure was Movement Time (MT), which was calculated as 3000 ms divided by the number of taps (Fitts, 1954). Error taps during each trial was counted by the investigator and the number of counts was analyzed since there is a tradeoff relationship between the speed and accuracy of the movements. Lastly, since the instruction for the present study specifically asked participants to aim at the center of the target, the precise accuracy of multiple taps for each trial was measured for the confirmation purpose of the given instruction. Precise accuracy of multiple taps was measured in two methods: Mean Radial Error (MRE) and Bivariate Variable Error (BVE) (Hancock et al., 1995). MRE represents the general accuracy and BVE represents variability of performance around the mean of hits. Both MRE and BVE were measured by identifying the distance between the center of the target to the center of the stylus at each hit.

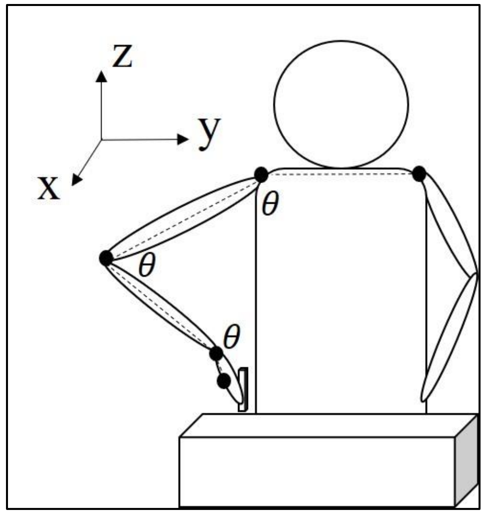


Figure 5.1. Marker Placement and Joint Angle Determination.

Statistical Analysis

Performance measures regarding MT and error taps were described in Chapter IV. Specifically, the testing phase was measured with a 3 (Group) x 3 (ID) x 3 (Time: Baseline, 5-minute, 48-hour retention tests) ANOVA with repeated measures on the last two factors. The practice phase was measured using a 3 (Group) x 3 (ID) x 4 (Block) ANOVA with repeated measures on the last two factors. Since the transfer test was a dual task procedure, this phase was separately analyzed with a 3 (Group) x 3 (ID) ANOVA with repeated measures on the second factor. For MRE and BVE, the average of the right and left target (combined accuracy and consistency) is used to represent the general motor learning about the precise accuracy and analyzed between testing phases (3 x 3 x 3 ANOVA for baseline and retention tests and 3 x 3 of group x ID ANOVA for the transfer test). Since MRE and BVE are not the primary variable and used for a confirmation purpose, the results are not discussed in the discussion.

For CV, SD, and SamEn, a 3 (Group) x 3 (ID) x 3 (Time) x 3 (Joint) ANOVA with repeated measures on the last three factors was used for the practice phase. The transfer test was measured using 3 (Group) x 3 (ID) x 3 (Joint) ANOVA with repeated measures on the last two factors. Alpha was set at .05 *a priori* for all analyses. *Post hoc* tests were conducted, if necessary, with Bonferroni correction at alpha level of .05. When there was a violation of sphericity in the main analyses, a Greenhouse-Geiser correction was used to interpret the results. Effect size were qualitatively interpreted as partial eta squared (η^2_p) = .011 to .05 as small, .06 to .13 as medium, and .14 as large (Cohen, 1988). Effect size ≤ .01 is interpreted as N/A since it is negligible effect size.

During the acquisition phase, participants practiced three trials for each ID with random order compared to the testing phase in which participants performed one trial for each ID in a specific order. During the acquisition phase, a time factor within each ID (learning effect; fatigue effect by repeating the same ID trials multiple times) is wrapped in another time factor between different ID conditions (learning effect by the acquisition phase procedure). Due to these differences between the acquisition and testing phases, the acquisition phase was only qualitatively described. Thus, the results of the acquisition phase were excluded from the discussion.

Results

Performance

For MRE and BVE, the detail of statistical results and performance mean and SD are summarized in Appendix L. Although MRE and BVE in ID was significant, it was larger for the ID_{low} condition relative to the difficult conditions. Since there is a limit of error, MRE and BVE were influenced by the size of the target (*i.e.*, ID = 2 had 6 x 6 cm, and thus more space for error). An important finding was that a significant group difference was found in the transfer test ($F_{2,57} = 3.46$, $p < .05$, $\eta^2_p = .11$) in BVE in that the INF had a larger BVE than the CON group, which confirmed the results of the error taps in the transfer test.

SD of Angular Velocity

The statistical results and figures of the mean angular velocity are summarized in Appendix M. As shown in the figure of Appendix M, the joint angular velocity increased with time, the greatest velocity at the shoulder joint, and greater velocity during more difficult conditions.

Detail of statistical results of SD angular velocity is summarized in Appendix N. Significance results were found in ID ($F_{1.32,75.19} = 814.16$, $p < .01$, $\eta^2_p = .93$), time ($F_{1.46,83.03} = 29.78$, $p < .01$, $\eta^2_p = .34$), joint ($F_{2,114} = 16.34$, $p < .01$, $\eta^2_p = .22$), interaction between ID and joint ($F_{2.33,133.03} = 55.21$, $p < .01$, $\eta^2_p = .49$), and time and joint ($F_{2.93,166.97} = 7.96$, $p < .01$, $\eta^2_p = .12$). The detail of statistical results is shown in Appendix M. *Post hoc* tests on the ID and joint interaction by analyzing between joints at each ID revealed that, at the ID_{low} condition, there was no difference between the shoulder (*M* = 9.31 deg/sec, *SD* = 3.00) and elbow joint (*M* = 9.67, *SD* = 3.00), $p > .05$, but the variability of the shoulder and elbow angular velocity was higher than the wrist joint (*M* = 7.05, *SD* = 2.07), $p < .01$ for both. In the ID_{med} condition, the shoulder variability (*M* = 14.94, *SD* = 4.50) was higher than both elbow (*M* = 12.23, *SD* = 3.58) and wrist joint (*M* = 11.47, *SD* = 3.67). In the ID_{high} condition, the shoulder (*M* = 24.54, *SD* = 6.46) and wrist joint angular velocity (*M* = 21.91, *SD* = 5.62) was higher than the elbow (*M* = 17.78, *SD* = 4.00), $p < .01$, while the shoulder variability was even higher than the wrist joint, $p < .05$ (Figure 5.2top). Analyzing across ID's by each joint, all joints showed significantly higher SD in the ID_{high} relative to the ID_{low} and ID_{med} ($p < .01$ for all) (Figure 5.2 top). *Post hoc* tests for the time by joint interaction by analyzing the differences between time points at each joint revealed that there is no difference across time in the shoulder joint (*M* = 15.94, *SD* = 4.43; *M* = 16.31, *SD* = 4.88; *M* = 16.45, *SD* = 4.85, for the baseline, 5-minute retention, 48-hour retention test respectively), but at the elbow and wrist joints, the baseline (*M* = 12.02, *SD* = 3.01 for elbow; *M* = 11.63, *SD* = 3.41 for wrist) was significantly lower than the 5-minute retention (*M* = 13.58, *SD* = 3.41 for elbow; *M* = 13.85, *SD* = 4.26 for wrist) ($p < .01$ for both), and the 48-hour retention, and the 5-minute retention test was significantly lower than the 48-hour retention test (*M* = 14.07, *SD* = 3.47 for elbow; *M* = 14.96, *SD* = 4.12) ($p < .05$ for elbow, $p < .01$ for wrist). Analyzing between joints at each time point, the shoulder joint SD was higher than the elbow and wrist joint ($p < .01$) where no difference was found between the elbow and wrist ($p > .05$) in the baseline and 5-minute retention tests. However, during the 48-hour retention test, only the elbow SD was lower than the shoulder and wrist ($p < .01$), whereas no difference was found between the shoulder joint and wrist (Figure 5.2 bottom). In the transfer test, a significance was found only in ID ($F_{1.00,57.14} = 6.94$, $p < .01$, $\eta^2_p = .11$). *Post hoc* test on ID showed that the ID_{low} condition was lower than the ID_{med} condition ($p < .01$) and the ID_{high} condition ($p < .05$), but no difference was found between the ID_{med} and the ID_{high} condition ($p > .05$).

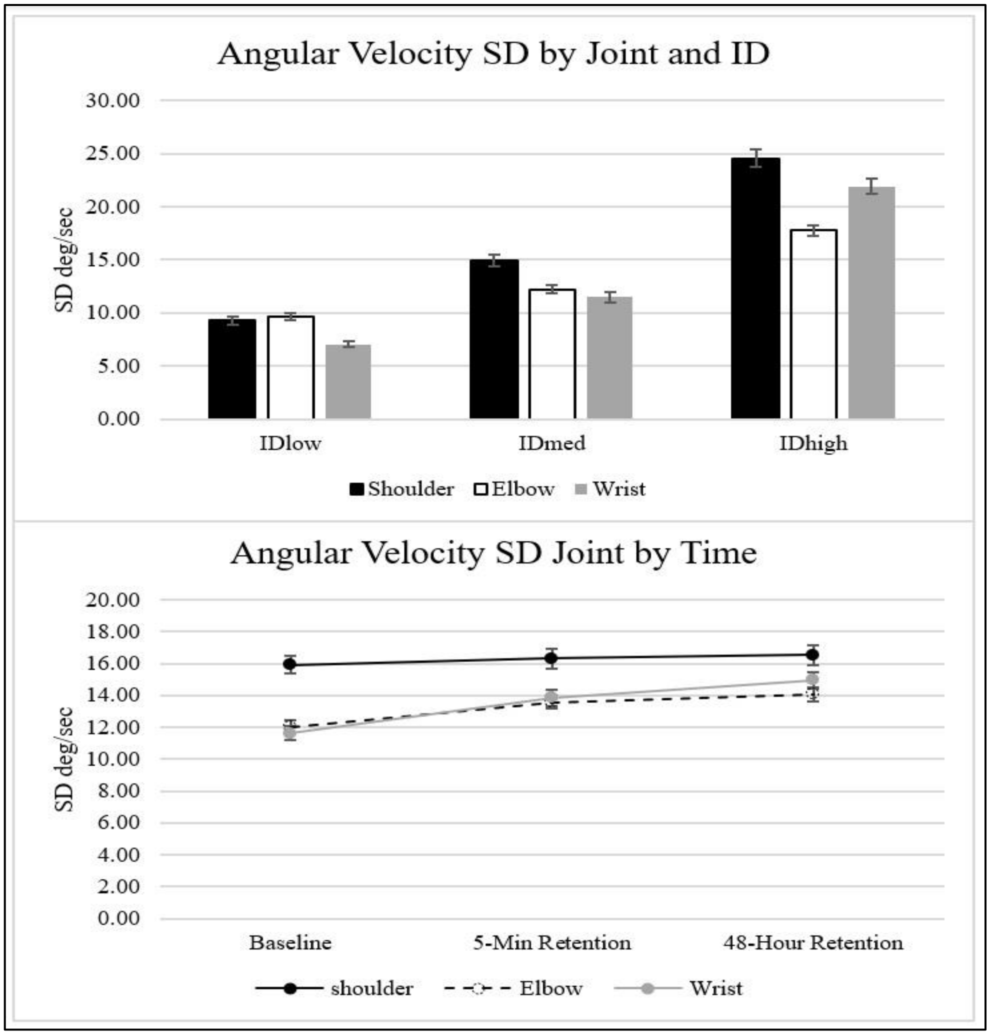


Figure 5.2. SD of Angular Velocity. The top figure shows the interaction effect between time and joint and the bottom figure shows the interaction between ID and joint. The bottom figure shows the marginal means of each ID of baseline, 5-minute retention, and 48-hour retention tests. Bar represents SEM of within-subject factor. Ret = retention test.

CV of Angular Velocity

There were significance in ID ($F_{1.40,79.78}$ = 588.01, p < .01, η^2_p = .91), time ($F_{1.38,78.66}$ = 53.59, p < .01, η^2_p = .49), joint ($F_{1.76,100.42}$ = 149.23, p < .01, η^2_p = .72), interaction between ID and time ($F_{2.52,143.39}$ = 3.12, p < .05, η^2_p = .05), between ID and joint ($F_{2.71,158.49}$ = 52.52, p < .01, η^2_p = .48), and between time and joint ($F_{13.24,133.09}$ =

14.04, $p < .01$, $\eta^2_p = .20$). *Post hoc* tests for the interaction effects between ID and joint showed that, at the ID_{low} and ID_{med} conditions in the baseline, the shoulder angular velocity CV was lower than the elbow and wrist joints, where no difference was found between the elbow and wrist joints ($p > .05$), but there was no difference across the joints for the ID_{high} condition. At the 5-minute retention test, the shoulder angular velocity CV was lower compared to the elbow ($p < .01$) and elbow was lower than the wrist joint ($p < .01$ and $p < .02$, for ID_{low} and ID_{med}, respectively) in the ID_{low} and ID_{med} conditions, but there was no difference across the joints for the ID_{high} condition. In the 48-hour retention test, the shoulder joint CV was smaller than the elbow joint, and the elbow joint was smaller than the wrist joint were all different ($p < .01$ for all) for the ID_{low} and ID_{med} conditions, but the wrist CV was higher than the shoulder and elbow CV (both $p < .01$) for the ID_{high} condition (Figure 5.3). As shown in Figure 5.3, the changes in the CV across time were not obvious in the ID_{low} and ID_{med} conditions for the elbow and wrist, while the shoulder CV showed a decrease in CV in all difficulty conditions. This decrease in CV was also evident in the elbow and wrist joint for the ID_{high} condition. *Post hoc* tests on time factor confirmed that, at the wrist joint, no change was shown at the ID_{low} and ID_{med} conditions ($p > .05$) throughout the experiment, but the wrist CV decreased from the baseline to the 5-minute and 48-hour retention tests for the ID_{high} condition ($p < .01$ for both). For the elbow and shoulder joints, a significant decrease in CV was evident from the baseline to the 5-minute and 48-hour retention tests (both $p < .01$) with no difference between the two retention tests ($p > .05$) for all difficulty conditions.

In the transfer test, significance was found in ID ($F_{1.08,61.56}$ = 81.80, p < .01, η^2_p = .59) and joint ($F_{1.05,59.79}$ = 13.95, p < .01, η^2_p = .20). *Post hoc* tests showed that the wrist and elbow joints variability was higher than the shoulder joint (p < .01), where no difference was found between the wrist and elbow (p > .05). The variability at the ID_{high} condition was lower than the ID_{low} and ID_{med} conditions (p < .01), and the ID_{med} condition was lower than the ID_{low} condition (p < .01). Although nonsignificant, the results of the group factor showed a medium effect ($F_{2,57}$ = 2.17, p = .12, η^2_p = .07), while all other analyses resulted in small effect size. Interestingly, the INF group had a lower CV (*M* = .83, *SE* = .03) than the CON group (highest CV amongst the groups) (*M* = .91, *SE* = .03), while the EXF was in between the two groups (*M* = .83, *SE* = .03), which exhibited the same pattern of the error taps. The details of statistical results are shown in Appendix N.

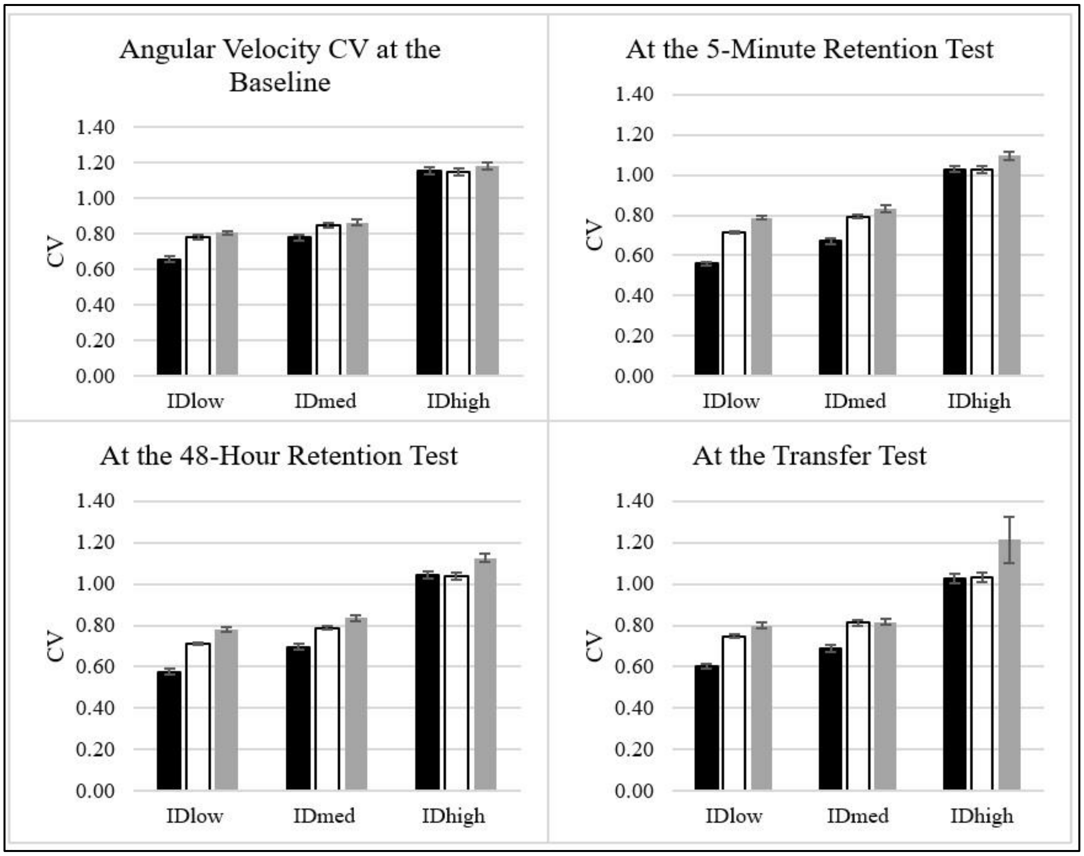


Figure 5.3. CV of Angular Velocity (ID by Joint) for Different Testing Phases. Black = Shoulder joint; White = elbow joint; gray = wrist joint. Bar represents SEM of within-subject factor.

SampEn of Angular Velocity

Following processing the data, two potential concerns that may challenge the interpretation of the results became evident. Although the number of data points were identical across participants, ID, and time, the number of strokes of flexion/extension was clearly different. Specifically, the sinusoidal waves of flexion and extension was evidently greater for a lower ID due to a lower MT. Since the similarity of the continuous pattern of movements are measured, this may affect the SampEn output. Therefore, we analyzed a Pearson correlation between MT and SampEn output of the shoulder joint for each ID at the baseline, given that a high correlation indicates the influence of the number of strokes. The results showed a poor correlation between MT and SampEn of the easy condition (r = .12, p = .36), medium condition (r = -.14, p = .30), and high condition (r < .01, p = .99). Another concern was that SampEn outputs were generally higher than previously reported studies (*e.g.*, Diekfuss et al., 2018; Rhea et al., 2019; Wijnants, Bosman, Hasselman, Cox, & Van Orden, 2009). A SampEn output of zero indicates that a signal is a sine wave, which is completely predictable and rigid (*i.e.*, low variability) and an output that is high implies that the signal is more unpredictable and complex. Therefore, an output that is too high may simply indicates a random signal (*i.e.*, Gaussian noise) than a stochastic signal, although the output of SampEn may be unique to the task and study design. Accordingly, we sampled randomly three trials from the ID_{high} condition of the same day, randomize the temporal order of the angular velocity of these trials, and ran SampEn, with same m and r, to qualitatively compare the difference of SampEn outputs of the obtained data and randomized data. Random choice using MATLAB resulted in P(participant) 59, the third trial of Block 3 at the shoulder joint; P55, the first trial of Block 3 at the shoulder joint; and P23, the first trial of Block 3 at the wrist joint were selected. Normal SamEn was .70, .50, and 1.65, for P59, P55, and P23, respectively. SampEn of the randomized data were 3.80, 3.45, 3.52, for P59, P55, and P23, respectively. This indicates that a Gaussian noise represents an output that is approximately around 3.5 or higher. Therefore, high SampEn outputs in the present study are not Gaussian noise. Consequently, statistical analysis was proceeded as hypothesized.

The detail of the statistical results is summarized in Appendix N. The results showed that significance was found in ID ($F_{1.82,\ 103.64}$ = 15.36, p < .01, η^2_p = .21), time ($F_{1.60,\ 91.00}$ = 696.40, p < .01, η^2_p = .92), joint ($F_{2,\ 114}$ = 423.06, p < .01, η^2_p = .88), interaction between ID and joint ($F_{3.14,\ 178.71}$ = 4.15, p < .01, η^2_p = .07), joint and group ($F_{4,\ 114}$ = 2.56, p < .05, η^2_p = .08), time and joint ($F_{3.19,\ 181.89}$ = 97.53, p < .01, η^2_p = .63), and three way interaction between time, joint, and group ($F_{6.38,\ 181.89}$ = 2.54, p < .05, η^2_p = .08), and ID, time and joint ($F_{5.10,\ 290.42}$ = 3.70, p < .01, η^2_p = .06). To map the source of difference between the two three-way interactions, Figure 5.4. shows time and joint by each group and Figure 5.5. shows time and joint by each ID. For *post hoc* tests for of 3 (Joint) x 3 (Time) ANOVA with repeated measures for each group with pairwise comparisons showed that all groups had a difference in joint, showing the shoulder entropy was lower than the elbow and wrist, and elbow entropy was lower than the wrist entropy (p < .01 for both) and had no interaction between the joint and time (p > .05). The source of interaction was evident in time, showing that the CON group did not change in SampEn from the baseline to both retention tests (p > .05), while the INF and EXF groups had a decrease in time from the baseline to the retention tests (p < .01 for both 5-minute and 48-hour retention tests). For *post hoc* tests of the three-way interaction between time, ID, and joint, 3 (Joint) x 3 (Time) ANOVA with repeated measures for each ID with pairwise comparisons was conducted. Results showed that, at the ID_{low} condition, the interaction effect was detected: The shoulder joint decreased SampEn only between the baseline and 48-hour retention test (p < .01); at the elbow joint, SampEn was lower in both 5-minute and 48-hour retention tests (p < .01 for both) compared to the baseline, where no difference was found between the two retention tests (p > .05); and at the wrist joint, no difference was found between the baseline and 5-minute retention test nor 48-hour retention test (p > .05 for both), but SampEn reduced from the 5-minute retention test to the 48-hour retention test (p > .05) (Figure 5.5 top). For the ID_{med} condition, without interaction, SampEn decreased from the baseline to the 48-hour retention test (p < .05), but no difference was found between the baseline and 5-minute retention test (p > .05); and the shoulder joint SampEn was lower than the elbow, and the elbow SampEn was lower than the wrist SampEn (both p < .01) (Figure 5.5 middle). Lastly at the ID_{high} condition, there was an interaction effect between the joint and time (p < .05): The shoulder joint did not change from the baseline to the two retention tests (p > .05 for both); at the elbow joint, SampEn showed a significance changes in time (p < .05), but pairwise comparisons after adjusting the p-value failed to show the reduction of SampEn from the baseline to the 48-minute retention test (p =.06), and further reduction of SampEn from the 5-minute to 48-hour retention test (p = .08) (Figure 5.5 bottom).

During the transfer test, significance was found in time ($F_{1.36,\ 77.72}$ = 115.14, p < .01, η^2_p = .67), joint ($F_{1.64,\ 93.62}$ = 147.22, p < .01, η^2_p = .72), and interaction between ID and joint ($F_{1.57,\ 89.62}$ = 13.01, p < .01, η^2_p = .19). *Post hoc* tests showed that at all ID conditions, all joints were significantly different (all p < .01) and at all joints, SampEn was higher in the ID_{low} than the ID_{med}, and the ID_{med} than the ID_{high} conditions (all p < .01) (Figure 5.6). We believe that the source of the interaction effect is the magnitude of SampEn reduction at the wrist joint was greater than the other two joints.

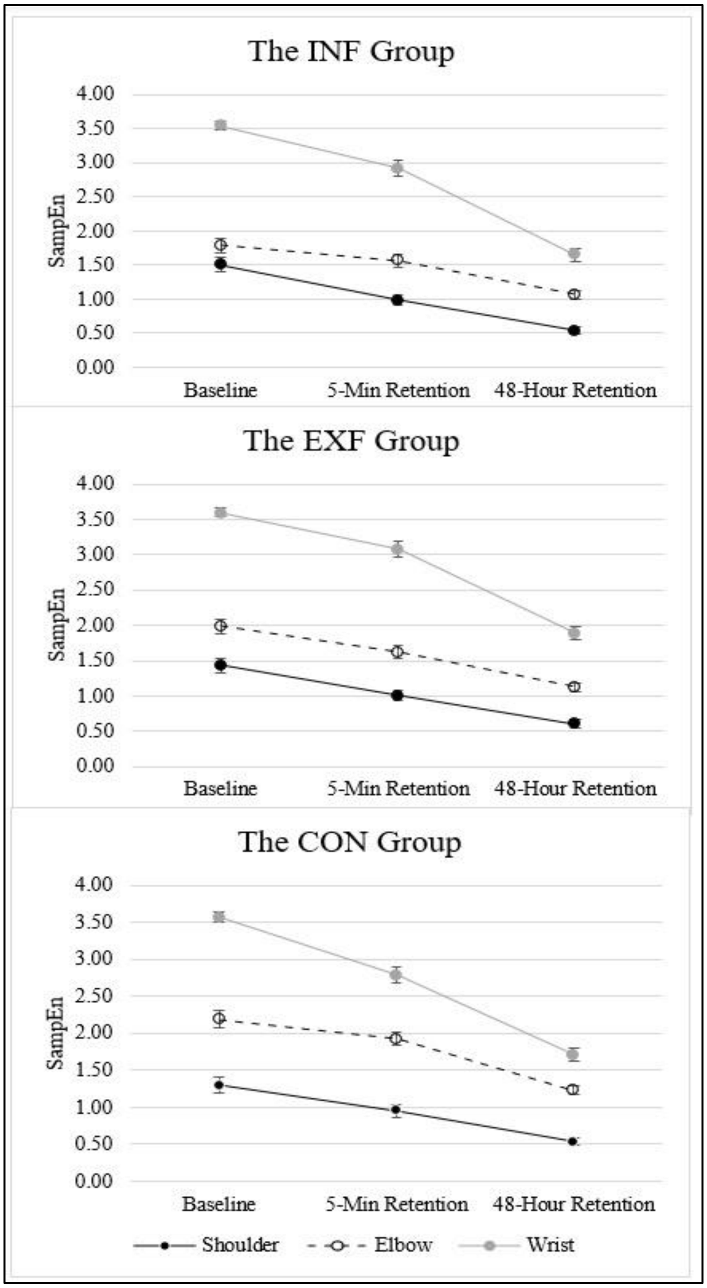


Figure 5.4. SampEn of Time by Joint for Each Group. Three-way interaction between time, joint, and group factors. Bar represents SEM of within-subject factor.

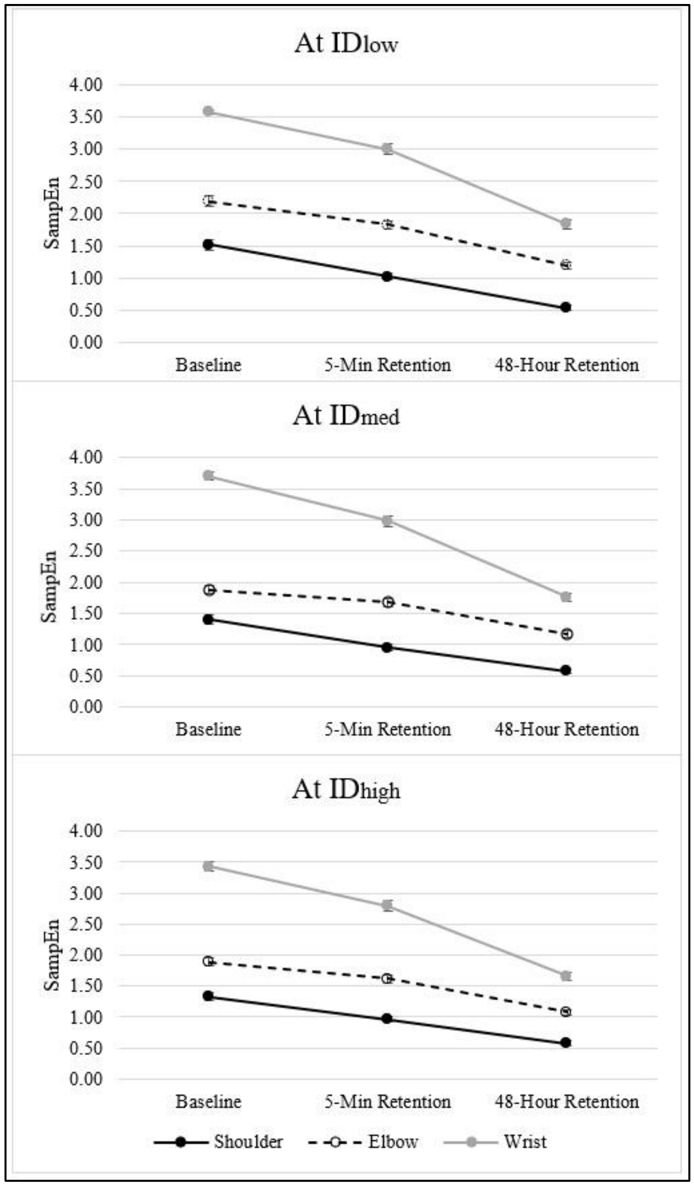


Figure 5.5. SampEn of Time by Joint for Each ID. Three-way interaction between time, joint, and ID factors. Bar represents SEM of within-subject factor.

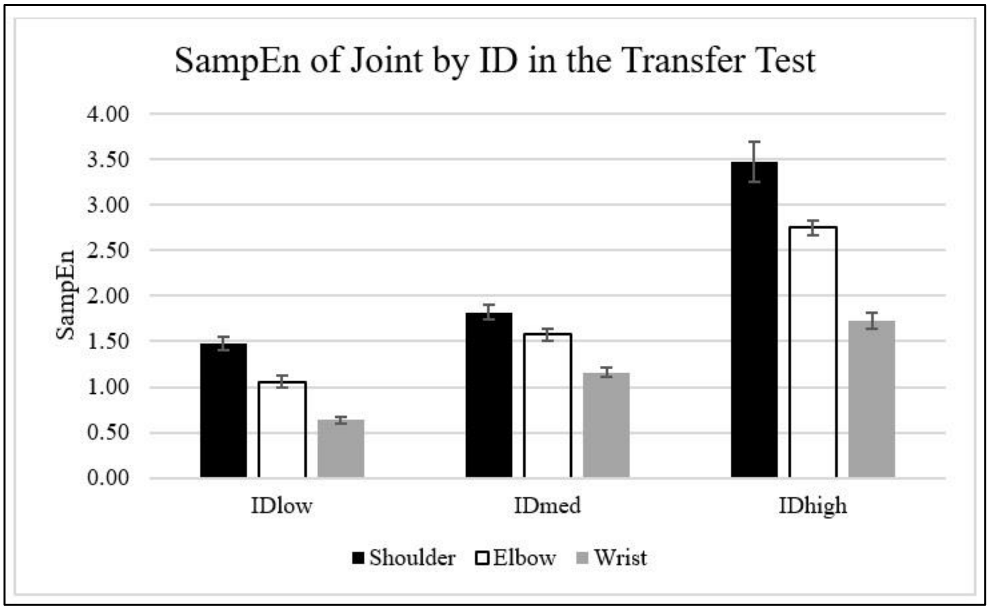


Figure 5.6. SampEn of Joint by ID in the Transfer Test. Bar represents SEM of within-subject factor.

Discussion

The present study examined variability as the magnitude of variability (SD and CV) and structure of variability (SampEn) to understand the potential mechanism of attentional focus and how variability changes by practice and task difficulty. For the attentional focus effects, it was hypothesized that the EXF group would have a higher variability relative to the INF group. For the learning effects, it was hypothesized that the variability would increase following practice. For task difficulty, it was hypothesized that variability would be higher in the more difficult conditions relative to the easier conditions. For the joint, it was hypothesized that variability of the distal segment would be greater while the proximal segment would show more fixed (low) variability.

Performance and Mean Angular Velocity

Examining the learning effect (baseline to the retention tests comparison), participants improved with the task in MT, and the more difficult conditions resulted in a slower MT compared to the easier conditions (Manuscript I). Thus, as expected, the task difficulty manipulation was successful and there was a learning effect. However, no group difference was evident in any ID's and phases of the experiment; This pattern was similar for error taps except for the transfer test; In the transfer test, the INF group showed a marginal effect to have a greater number of error taps relative to the CON group (Manuscript I). This difference was confirmed by analyzing precise performance variability (BVE), showing that performance variability was significantly higher in the INF group than the CON group. This suggests that the increased number of error taps in the INF group may be due to the difference in the performance variability. Lohse et al. (2013) discusses that an EXF promotes compensatory variability in bodily dimensions, which leads to a reduced performance variability. As a result, attentional focus effects may be more sensitive to variability than accuracy. The present study partially supported this proposition by showing an increased variability in the INF during the transfer test. Therefore, the present results along with Lohse et al. (2013) indicate that attentional focus affects movement variability, which, in turn, affects performance variability.

To interpret the results of the movement variability, it is important to understand the general pattern of the mean angular velocity change. The results showed that the angular velocity increased as performance improved, which is not surprising considering the increase in MT. Further, the velocity was highest in the distal (*i.e.*, shoulder) joint than the proximal (*i.e.*, wrist) joint and highest in the most difficult condition. These results were also expected since the shoulder joint moves the largest range of motion, serving as a primary mover during the reciprocal tapping task, and the most difficult condition had more distance to move.

SD and CV of Angular Velocity

The results of the SD of the angular velocity showed that while performance improved and angular velocity increased, the SD of the angular velocity increased in the retention tests relative to the baseline (at the elbow and wrist joints), which supported the hypothesis regarding the variability of the learning effects. The variability was greater in the distal (*i.e.*, shoulder) joint than the proximal (*i.e.*, wrist) joint, which also supported the hypothesis regarding the joint. The hypotheses about the attentional focus effects and difficulty were not supported: There was no difference between groups and interaction between any joints, ID, or time. Lastly, our hypothesis regarding ID was supported, showing that the more difficult conditions resulted in a greater SD variability.

Prior to the interpretation of these results, it is important to compare the results of SD with the variability as CV. The results showed that, with time, CV decreased only in the most difficult condition at the wrist joint and decreased in all difficulty conditions for the shoulder and elbow joints, which did not support the hypothesis (*i.e.*, the hypothesis was *to increase* variability). Regarding joints, variability of the wrist joint than the shoulder joint at the two easier conditions, which was the opposite to the results of SD. Therefore, the hypothesis regarding the joint was not supported. For the attentional focus effects, the hypothesis was not supported. However, when a difference between groups emerged in performance (*i.e.*, the increased error taps in the INF group relative to the CON in the transfer test), the results showed a marginal effect in the INF group relative to the CON group, suggesting that the INF had a lower CV than the CON group.

Movement variability and joint

The present study showed the different results between SD and CV at different joints with interactions between joint and time and joint and ID. In the baseline (no attentional focus cue presented), the distal joints exhibited the greater SD relative to the proximal joint. Interestingly, there was a gradual increase of SD in the proximal joint. However, this general trend of joint relationship in SD variability was the opposite for CV. In the baseline, the proximal joints CV were higher than the distal joint. Additionally, this opposite pattern was evident only in the two easier conditions and no difference was evident in the most difficult condition. When examining the variability as SD, the present study seems to indicate that the joint with a bigger musculature (and more motor units) possessed greater variability. This is congruent with one of the models of motor control mechanism in aiming tasks, known as Impulse Variability Model (Meyer et al., 1988; Schmidt et al., 1979). This model explains that noise increases with increased motor unit recruitments; therefore, the end point variability increases as ID increases due to an increased requirement of the larger and more musculature recruitment. Differences in variability can be considered from the degrees of freedom perspective. Mechanically, the shoulder joint has greater degrees of freedom than the other joints. If the increase or decrease in variability is dependent upon the number of degrees of freedom, CV should also be higher in the shoulder joint. However, when CV is considered, this proposition is not supported. A more recent study showed that the system noise *decreased* with an increase of movements that require stronger muscles (*i.e.*, more motor units) (Hamilton, Jones, & Wolpert, 2004). Hamilton et al. (2004) explains that stronger muscles are more active and lower firing rates compared to small muscles (in the fingers and wrist) that have less active motor units and higher firing rates. Higher firing rates cause more noise. Consequently, even though the absolute value would be smaller in small muscles, the relative variability (*i.e.*, CV) would be higher than bigger and stronger muscles. This result fits the profiles of the results of the present study. Additionally, Hamilton et al. showed that CV exponentially declined as the maximum voluntary contraction torque increased. This indicates that when performers produce less torque, the differences in variability between smaller and larger muscles would be clearer, but as the torque increases, there is a sharp decline in CV, the differences in CV between large and small muscles become ambiguous. Although the dependent variable was the joint angular velocity variability, the present study was in line with the findings by Hamilton et al. (2004). There was no difference in CV between the joints in the most difficult condition where the mean angular velocity was higher where a clear difference between joints were evident when the velocity was lower during the easier conditions. However, it is important to note that there were experimental distinctions between the present study and the study conducted by Hamilton et al. (2004) since that study examined neuromuscular activity and torque. Future studies should be directed to examine the connection between kinematic and kinetic variables in motor control. Thus, a more approachable explanation with the present data may be related to the 'roles' of each joint. In the task used in the present study, the wrist joint may serve as the correction of the stylus orientation, and the shoulder joint may serve primarily as the mover. To aid accuracy at the distal segment, producing a cyclic and constant motion may be optimal at the shoulder joint, while the wrist joint may require more subtle adjustments. As a result, the proportion of the shoulder joint variability was smaller and the wrist variability was higher, which also explains the increased variability at the wrist joint during the most difficult condition.

Another potential explanation may be derived from the information process perspective. A previous study examining Fitts' Law that uses smaller muscles (finger and wrist joints) and larger muscles (elbow and shoulder joints) showed that MT was faster in the task that requires smaller muscle relative to the task that required larger muscles even though ID's were relatively matched between the two tasks (Langolf et al., 1976). The information capacity is traditionally measured as Index of Performance (IP) (Fitts, 1954), where IP = ID/MT. Langolf et al. concluded that the distal segment has greater capacity due to a greater IP relative to the proximal joint, and different segments contain different information processing capacity. Increasing capacity indicates increasing the movement speed at a given ID. Because of the speed-and-accuracy tradeoff, the distal segment noise would increase with an increase of MT. As a result, it is possible to consider that variability was higher in the distal segment that requires smaller muscles. However, this hypothesis is based on the performance outcome. Additionally, the noise was determined by the size of the target (*i.e.*, W), rather than the actual variability produced by its performance. Accordingly, variability in the information process does not reflect the variability of the human motor system (Flach, Guisinger, & Robinson, 1996; Schmidt, Zelaznik, & Frank, 1978). Schmidt et al. (1978) proposed to post-evaluate W based on the performance variability to be comparable for motor control theories. However, little studies have examined how performance variability affects movement variability in Fitts' reciprocal tapping task. Future studies should be directed to examine the relationship of joint and performance variability where ID is calculated based on performance variability.

Movement variability and learning

The results were inconsistent regarding the learning effects. In the present study, as participants improved the task, the changes in the joint displacement over time became more variable in SD. The results seemed to support the previous studies of "freeing the degrees of freedom" of the movement coordination (Bernstein, 1967; Verejiken et al., 1992), which is indicative of a greater adjustment of the inherently noisy human systems (Davids et al., 2003; Stergious & Decker, 2010). However, for CV, variability *decreased* at the shoulder and elbow joints, which resulted in the opposite outcome compared to SD. The present study examined both variability as SD for a direct comparison from previous studies, proposing that variability of joint movements (as SD) increases with performance improvements (*e.g.*, Verejiken et al., 1992). However, it was expected that the amplitude of movements (*i.e.*, the joint angular velocity mean) would increase with performance improvements. Since the mean increases, it is natural that the corresponding SD increases. Additionally, variability as SD contains all the noise exists in the experimental setting. As a result, an increase or decrease in variability may be due to factors that are not related to the mean amplitude. However, examining the changes in variability, considering the changes of the mean amplitude (*i.e.*, CV), the increase or decrease in variability can be derived (more confidently) from the changes the amplitude mean. Accounting, the results of the present study suggest that variability as CV may represent motor learning more appropriately than SD. In support of the present results, Pohl, McDowd, Filion, Richards, and Stiers (2006) in arm movements and Tsao and Hodges (2008) in walking have shown that CV decreases with motor learning (although motor 're-learning' in these studies). Although Bernstein's original learning model indicates only an increase of variability (Bernstein, 1967), the dynamical system theory predicts that motor behavior is shaped by constraints towards an attractor state (Kelso, 1984; Milton, Small, & Solodkin, 2004; Newell, 1986; Newell & Vaillancourt, 2001). In a reciprocal tapping task, producing constant movements leads to an energy efficient movement pattern (*i.e.*, attractor state), and therefore may contribute to the decreased proportion of the joint angular velocity variability. Empirical evidence supports that the direction of variability change (increase or decrease) is dependent on the task goal (Ko, Challis, & Newell, 2003; Newell, Kugler, van Emmerik, McDonald, 1989). Although this is beyond the scope of the present study, the present results do not deny the freeing of degree of freedom with motor learning. As we indicate above, the increase or decrease in CV may be attractor specific, and thus it may not be the same for motor skills that prefer a different attractor. Further, the present study examined variability of each joint independently. In the case of examining *coordination* variability that examines the relationship of variability between different joints, research has shown that exploiting available degrees of freedom (Verrel, Pologe, Manselle, Lidenberger, & Woollacott,

2013) led to a greater performance. Two joints can compensate with each other, such as joint positioning, angles, and velocity in a three-dimensional area, to produce the same performance variability (See the uncontrolled manifold concept or UMC for Scholtz & Schöner, 1999). Future studies should be directed to examining the relationship between the interpretation of movement variability at each joint and coordination variability.

Movement variability and task difficulty

Results showed that variability was generally higher in the more difficult conditions. In the present study, the distance between the two targets was 32cm for the most difficult condition, and the distance was reduced by half for the medium (*i.e.*, 16cm) and easy (*i.e.*, 8cm) conditions. Accordingly, variability, especially in SD, would increase because the mean amplitude increased as ID increased due to the requirement of greater movements. Additionally, as ID increased, the target size became smaller. Thus, the requirement for movement correction may have increased with an increase in difficulty. These two factors may serve the increase in variability of the joint angular velocity. An important consideration is that whether different factors differently affect difficulty. In Fitt’s Law, difficulty is manipulated by the size of the target and distance. While Hamilton et al. (2004) showed how the number of motor unit recruitment and force amplitude requirement changes variability, which may support the changes in variability regarding the distance between the targets (since greater distance requires greater motor units), variability may be affected by the changes in the target size. This indicates that different factors of difficulty may differently affect movement variability. While performance outcome (*e.g.*, MT) differences by different IDs reflect on the mixture of the size and distance factor, examining movement variability may reveal the role of variability by examining variability of different joints.

Differences in variability by task difficulty can be interpreted from the Fitts Law paradigm. Previous research has shown that an easier cyclical tapping motion resulted in a faster movement speed and is distinctive from discrete tapping tasks, while more difficult cyclical task (*i.e.*, higher ID) resulted in slower movements; consequently, each tap became more similar to concatenation of discrete taps (Guiard, 1993; Smits-Engelsman, Van Galen &, Duysens, 2002). A discrete aiming exhibits more corrective behavior than a reciprocal tapping task (Huys, Fernandez, Bootsma, & Jirsa, 2010) while a reciprocal tapping task (when it is relatively easy) utilizes the exchanges of potential and kinetic energy at the moment of hit and the transition of the reversal movement, minimizing the energy cost (Guiard, 1993). Therefore, in a cyclical tapping task, as the task becomes easier, kinematics shows less corrective motion and requires less information capacity, which leads to greater performance (*i.e.*, greater ratio of ID to MT, which is known as Index of Performance or IP). The results of the present study support these ideas by showing that the joint angular velocity variability was lower for the easier tasks in both SD and CV. The changes in the general angular velocity variability may reflect energy efficiency of the movements.

Movement variability and attentional focus

Referring to performance data, the INF group showed an increased error relative to the CON (Manuscript I). Then, it is natural to expect that there would be a difference in the systems that produced its outcomes. However, not only in the mean angular velocity, the SD of angular velocity also did not exhibit any group difference. In contrast, there was a marginal group difference with a medium effect size in the CV of angular velocity. The reduction of CV with practice suggests that a lower CV is an indication of a ‘good’ movement characteristics. However, when CV was lower than the non-attentional focus strategy group, there was a detrimental effect of performance. Thus, too low movement variability as CV is an indication of poor performance. This result replicated the previous study, showing that too little or high variability was characteristics of poor performance (Brach et al., 2005). Traditionally, variability has been considered as an indicative of poor performance. However, the present study with numerous research in variability supported that some variability is necessary for an optimal motor control (Brach et al., 2005; Davids et al., 2003; Newell & Vaillancourt, 2001; Slifkin & Newell, 1999; Stergiou & Decker, 2005). Thus, when working memory was loaded by a secondary task, an INF attenuated this motor richness (*i.e.*, variable, and flexible movements) of the joint movements. Previously, Wulf et al. (2001) and McNevin et al. (2003) measured Mean Power Frequency (MPF) of a balance task under an INF and EXF condition and showed that an INF led to a smaller MPF (*i.e.*, less subtle postural adjustments) relative to the EXF condition. Thus, an INF caused the motor system to produce a more rigid movement pattern. This source of the rigid pattern may be linked to a poorer neuromuscular control. Previously, an INF has been shown to increase co-contraction rate (*i.e.*, simultaneous contraction of the agonist and antagonist muscles) (Lohse & Sherwood, 2012). While coactivation increases stability (*i.e.*, rigidity) of a joint (Baratta, Solomonow, Zhou et al., 1988), it decreases mobility as a tradeoff. Therefore, an INF may have affected the balance of agonist and antagonist contraction/relaxation, which is also critical in a reciprocal tapping task that requires a series of flexion and extension of the upper limb. It is important to note that the changes in variability by attentional focus was evident only in the relative changes (to its mean) variability (*i.e.*, CV) rather than the absolute changes in variability (*i.e.*, SD). This result replicated the finding of Rhea et al. (2019), showing that variability changes by attentional focus were sensitive to the measurement tools. The present study suggests that attentional focus may affect the proportion of variability.

SampEn of Angular Velocity

The results of SampEn were similar to the results of CV, specific to learning and joint. SampEn decreased with practice and SampEn at the proximal joint was greater compared to the distal joints. The results may be counterintuitive when compared to the previous findings. SampEn has been shown to decrease in an EXF with greater performance (Kal et al., 2013; Rhea et al., 2019), concluding that a greater SampEn indicates a stochastic process. However, SampEn decreased in other studies that adopted a more dynamic task using a wobble board (Diekfuss et al., 2018) or stabilometer (Vaz et al.,2019). Similar to the findings regarding the direction of increase or decrease of the magnitude of variability (Ko et al., 2003), Newell, Broderik, Deutsh, and Slifkin (2003) provided evidence that an increase or decrease of complexity in the structure of variability was also based on the task goal. Newell et al. showed entropy (as Approximate Entropy) increased for a task that requires a constant force following five days of practice, while entropy decreased for a task that requires variable force. The attractor state of the former task is similar to postural control or paced leg movements, while the attractor state of the latter task is similar to a balancing on an unstable platform to maintain a stable state against ever changing surface orientation. Thus, bidirectional changes of the degrees of freedom is crucial in the organization of the motor system. In an aiming task, previous studies showed that the temporal structure of performance variability decreased with practice (Wijnants, Bosman, Hasselman, Cox, & Van Orden, 2009). Therefore, the organization system of the aiming task would be to reduce the degrees of freedom for an optimal performance.

To our knowledge, the application of SampEn to movement kinematics has rarely been conducted (Srinivasan, Mathiassen, Samini, & Madeleine, 2005). Data used for SampEn measure (*i.e.*, angular velocity) for the present study was an exploratory measurement since the regularity or complexity of a temporal structure of variability is generally measured using a discrete times series of performance (*e.g.*, trial-to-trial fluctuations of stride length; timing of hitting keys). However, since hundreds to thousands of data points are required for an appropriate analysis of discrete times series variability (*e.g.*, SampEn) (Yentes et al., 2013), this method may limit investigation of motor control in frail populations to walk for a prolonged period or to isolate mental boredom effects. The latter concern is particularly important for attentional focus research since people's minds spontaneously shift or drift (*i.e.*, mind wandering) (Smallwood & Schooler, 2006). When motor skills require a relatively longer period of trials (*e.g.*, 5 minutes for each trial), studies have failed to replicate the attentional focus effects (De Melker Worms et al., 2017a; 2017b), potentially due to shifting attention to else than the assigned attentional focus cues. To overcome this potential shortcoming, the present study explored continuous time series variability of joint movements. If time series variability exists the temporal structure of performance variability, it is possible that the source of variability exists in the time series of movement control. A potential advantage of this method is that it may not require thousands of repeated trials. When examining, for example, the changes in the joint angular velocity of a reaching task and capture the movements with 100Hz with a motion capture system for 30 seconds, 3000 data points of the fluctuations of increasing and decreasing joint angular velocity are obtained. If this reflects motor learning, attentional focus, or other variables, this may develop the understanding of the relationship between motor behavior and variability in continuous and discrete time series variability of movement control. Given these considerations, the present study replicated the previous study (Srinivasan et al., 2005) that the temporal structure of performance variability may be evidenced from the temporal structure of movement variability. One may consider an inconsistency against a study that increased coordination variability (*i.e.*, Lohse et al., 2014 in a dart throwing task). Although both dart throwing and reciprocal tapping tasks are aiming tasks, the degrees of freedom are greater in dart throwing. In a reciprocal tapping task, participants move a stylus from a fixed point toward another fixed point in the different spatial coordinates. The stylus never leaves from the mover's hand. As a result, the degrees of freedom to be controlled primarily originates in the intrinsic system. Contrary, in a dart throwing, a mover is required to control the degrees of freedom of the dart as well as the degrees of freedom of the mover's intrinsic system. Further, since the dart would depart from the mover's hand, the temporal degrees of freedom is critical (*i.e.*, you would hit the target with a slower or faster movement in a reciprocal tapping but the trajectory of the dart is dependent upon both the spatial and temporal coordination in a dart throwing task). Thus, the optimal variability control in a dart throwing task may be to become able to compensate arrays of degrees of freedom (*i.e.*, increasing movement variability).

Comparing the results between SD, CV, and SampEn, there were more commonalities between CV and SampEn than SD. SampEn declined with practice and the proximal joint SampEn was higher than the distal segment. SampEn measures the temporal structure of regularity/irregularity of the signal. The present study showed that practice reduced the proportion of variability of the joint angular velocity. Although all joints decreased SampEn, the proximal joint maintained to be higher than the distal joints. Similar to CV, the differences in SampEn across the joints may be due to different primary roles of each joint in a goal directed aiming task. If the end point coordinate is dependent upon the interlimb coordination between the shoulder and elbow joints, the wrist joint serves as a final adjuster of the aiming task. Then, it is possible that the variability of the proximal segments is transmitted to the distal joint, resulting in a greater variability in the wrist joint (*i.e.*, variability of its own segment plus variability of the distal segment). Future studies should be directed to examine the *role* variability at different joint segments.

It is important to note that the SampEn output in the present study was larger when compared with the SampEn of other studies. While it is challenging to compare SampEn output due to differences, including the number of datapoints, type of the data (discrete or continuous), task, and performance variability versus movement variability. One potential explanation of this result was due to the parameters chosen for the present study. Previous study showed that smaller m and r increases SampEn output relative to a larger m and r (Montesinos, Castaldo, & Pecchia, 2018). The present study was distinctive from previous studies in that the use of SampEn on the continuous times series of the joint angular velocity, rather than a traditional method of examining SampEn of trial-to-trial fluctuation pattern of performance outcomes. Consequently, the present study lacks in comparison to estimate appropriate parameters. We determined the optimal window of m and tolerance (r) based on the recommendation (Lake et al., 2002) from a pilot data. However, we chose fixed parameters for all joints, task difficulty, and time point. The advantage of this method is that it allows us to compare the SampEn outputs for different time points, joints, and difficulties. However, the disadvantage of this method is that an optimal set of m and r may exist for different difficulty, joint, and skill level. This may have largely influenced a high SampEn output. Future studies should be directed to examine the effect of parameter changes on different joint segments and difficulties.

The results of SampEn did not show any group differences in any phase of the experiment. Although time series variability has been shown to be sensitive to the attentional focus manipulation (Kal et al., 2013; Rhea et al., 2019), other studies also did not find a difference (Vaz et al., 2019; Diekfuss et al., 2018). Therefore, the interpretation of the attentional focus effects on time series variability is limited due to the absence of performance difference in the retention tests. However, no difference was also evident in the transfer test when the INF group showed performance decrement. While there is lack of evidence to support the results, one potential explanation is that attentional focus effects on a time series variability may be expected based on the task goal. In the two studies that showed the attentional focus effects (Kal et al., 2013; Rhea et al., 2019), the higher SampEn indicated a better performance. It is possible that attentional focus effects may not be evident for motor skills that requires a reduction of time series variability for the optimal motor control. Future studies should be directed to consider the attentional focus effects and the direction of variability.

Conclusion

The present study investigated the effects of attentional focus, task difficulty, and practice on movement variability as SD and CV and time series variability as SampEn. Additionally, the present study examined the time series variability on continuous data of the movement coordination (joint angular velocity) as a preliminary study to examine whether the source of time series variability exists in the movement variability, instead of time series of performance variability. The results showed that greater variability of the joint angular velocity for more difficult task in all metrics, SD increased while CV and SampEn decreased with practice. Further variability as SD was higher in the shoulder joint than the other joints and the wrist joint was smaller than the other joints, but this pattern was opposite for variability as CV and SampEn. We believe that the magnitude of variability as SD is affected by its mean. Therefore, CV and SampEn may be more appropriate metrics to measure variability and motor learning. Lastly, the attentional focus effects may be sensitive to variability as CV by showing that the INF group showed *too little* variability relative to the CON group. This indicates that an INF caused a motor control pattern that is less adaptable and flexible, which may affect an increase of performance variability.

CHAPTER VI

THE EFFECTS OF FOCUS OF ATTENTION ON EXPLICIT KNOWLEDGE, MENTAL WORKLOAD, AND PERCEIVED COMPETENCE

Abstract

The theories regarding attentional focus effects on motor skill acquisition have proposed that attention to the effects of the movement (External focus, EXF) is beneficial due to enhanced automaticity (Wulf, 2013). Contrary, attention to body movements (Internal focus, INF) disrupts neuromuscular coordination (*i.e.*, the constrained action hypothesis) (Wulf et al., 2001) or micro-choking by inducing self-focus (*i.e.*, the OPTIMAL theory) (Wulf & Lewthwaite, 2016). Another theory in memory suggests that an INF disrupts working memory by increasing explicit knowledge, which is detrimental to motor learning (Poolton et al., 2006). To understand factors that mediate attentional focus effects, the present study examined mental workload, perceived competence, and the amount and types of explicit knowledge. The EXF (n = 20), INF (n = 20), and control (CON) (n = 20) groups practiced a reciprocal aiming task that varied in three task difficulties. A 5-minute and 48-hour retention tests with a dual task transfer test were administered to examine the learning effects and automaticity following two days of practice. Although group differences were not observed for performance during practice

and retention tests, the INF group showed a trending effect of an increasing error relative to the CON group in the transfer test. Mental workload and perceived competence paralleled the changes in performance, which did not mediate the attentional focus effects. However, a chi-square of independence with *post hoc* tests showed that the EXF group had a greater proportion of explicit rules about techniques and smaller proportion of self-focus thoughts relative to corresponding expected values, while the INF group had a lower proportion of explicit rules about techniques. The present study showed that an INF may be detrimental due to the deviation of thoughts from the task relevant features. Explicit knowledge may explain an underlying mechanism of attentional focus.

Introduction

Research in attentional focus has demonstrated that directing an individual's attention to the effects of the movement on the environment (External focus, EXF) is more beneficial in motor learning and performance than directing his/her attention to the body movements (Internal focus, INF) (Wulf, 2013). Previous research has consistently supported beneficial effect of an EXF over an INF in various motor skills, including the meta-analysis of studies in balance tasks (Kim et al., 2017), review of skills requiring muscular endurance and strength (Marchant, 2010), and balance and gait tasks in clinical settings and older adults (Ziv & Lidor, 2015). Currently, the constrained action hypothesis (CAH) (McNevin et al., 2003; Wulf et al., 2001a, 2001b) and the OPTIMAL theory (Wulf & Lewthwaite, 2016) render theoretical explanations of these effects. The CAH proposes that an INF disrupts the motor system by adding "noise" to the neuromuscular system (Zachry et al., 2004). Empirical evidence has shown that an INF increased neuromuscular activity with a lower produced force (Marchant et al., 2009) or poorer dart throwing (Lohse et al., 2010) and basketball shooting performance relative to an EXF (Zachry et al., 2004). These studies indicate that an INF invokes inefficient motor coordination. Contrary, an EXF promotes more automatic mode of coordination, such as a greater subtle postural adjustments during a balance task measured in mean power frequency (Wulf et al., 2001a), or smoother movements measured in jerk (the fourth derivatives of the knee displacement) (Kal et al., 2013). While the OPTIMAL theory supports the same explanation for the EXF effects, it proposes different explanations for the INF effects from the CAH. The OPTIMAL theory explains that an INF is detrimental since it promotes conscious control of movements, which disrupts the automaticity of movement coordination, known as "self-invoking trigger" (McKay, Wulf, Lewthwaite, & Nordin, 2015; Wulf & Lewthwaite, 2010). Research supported this proposition by showing an increased proportion of self-evaluative thoughts that cause micro-choking when individuals adopted an INF (Perreault & French, 2015). Therefore, for an INF effect, the CAH provides a functional explanation while the OPTIMAL theory proposes a cognitive explanation.

While abundant evidence has shown that EXF and INF affect neuromuscular coordination (Marchant & Greig, 2012; Lohse et al., 2010; Lohse 2012; Wulf & Dufek, 2010; Zachry et al., 2005), the underlying mechanism of this neuromuscular change is still unclear. For further theoretical development, one of the areas that is limited in the EXF/INF paradigm is investigation of subjective profiles. The majority of the evidence provided in the previous studies in the EXF/INF pardigm was based on performance outcome or functional evidence. Considering attentional focus affects thoughts about conscious control (Perreault & French, 2015), it is possible that the differences in functional control is affected by subjective profiles, which in turn affects performance outcomes. Therefore, understanding individuals' perception may provide additional and unique information to develop theories in attentional focus. To this end, an alternative explanation has been proposed by Maxwell and Masters (2002) and Poolton et al. (2006). According to Maxwell and Masters and Poolton et al., an EXF or INF affects how our memory is structured. Although different terms have been used by different researchers (Anderson, 1982; Berry & Broadbent, 1987, 1988), it is generally accepted that motor learning involves two types of memory; explicit and implicit knowledge *Explicit knowledge* is referred to as the facts and rules that can be articulated whereas *implicit knowledge* is referred to as rules in which an individual can perform the task (*i.e.*, knows how to perform) but cannot articulate the movement executions (Masters, 1992). It is believed that individuals first accumulate explicit knowledge; With practice, implicit knowledge predominates explicit knowledge (Anderson, 1982). This shift of knowledge is congruent with the learning theories based on the cognitive process (Fitts & Posner, 1967; Schneider & Shiffrin, 1977), proposing that the cognitive process at the initial learning stage is conscious and slow (*i.e.*, controlled process) while the process becomes more fast and requires little attention (*i.e.*, automatic process). Hence, a shift from a controlled to automatic process can be replaced with a shift from explicit knowledge to implicit knowledge (Anderson, 1982; Masters, 1992). However, researchers examining motor skills and explicit/implicit knowledge have shown that explicit knowledge may not be the necessary step of motor learning (Green & Flowers ,1991; Masters & Maxwell, 2008). A practice environment that promotes an accumulation of explicit knowledge (*e.g.*, providing the list of instructions about the motor skill execution) was detrimental relative to the implicit knowledge learning (*e.g.*, simply telling the learners to do their best; using an analogy instruction) especially under pressure or during dual-task (Koudejiker et al., 2007; Lam, Maxwell, & Masters, 2009; Maxwell, Masters, Kerr, & Weedon, 2001). Additionally, Poolton et al. (2006) found a link between memory and attentional focus. In that study, the INF condition resulted in greater amount of explicit knowledge about internally focused thoughts and the INF condition resulted in more errors in golf putting during a dual task (*i.e.*, transfer test). From these results, Poolton et al. (2006) proposed that an INF is detrimental not due to the disruption of the motor system but because an INF would lead to a greater amount of explicit knowledge, which consumes working memory. These results are in line with Perreault and French (2015) in that an INF provoked self-evaluative thoughts. However, Perreault and French (2015) qualitatively reported that an INF induces a particular *type* of thoughts among various types of thoughts reported in the manipulation check. Poolton et al. (2006) adopted inferential statistics and analyzed both amount and type of explicit rules, however, explicit rules were categorized only into INF or EXF. As a result, inter-relationship between EXF/INF and different types of explicit thoughts was unclear. This warrants further investigation regarding the effects of attentional focus on both *types* and *amount* of explicit knowledge.

In addition to explicit/implicit knowledge, other research tools have been investigated to understand the relationship between action and subjective profiles. One approach is a subjective mental workload. For example, NASA-Task Load Index (NASA-TLX) (Hart & Staveland, 1988) is a valid and reliable questionnaire that assesses mental and physical workload, stress level, effort, and sense of accomplishment (Hart, 2006). Research has shown that subjective mental workload increased when a motor skill was performed with a cognitive task (*i.e.*, dual task) (Diekfuss et al., 2017; Knaepen, Marusic, Crea et al., 2015) or increased as task difficulty increased (Akizuki & Ohashi, 2015; Knaepen et al., 2015; Shugi et al., 2017). Similarly, some researchers have shown that a subjective statement of personal ability (*i.e.*, perceived competence) (Fox, 1997) increased with practice and decreased with difficulty of the given task (Frikha et al., 2019). These studies suggest that motor skill learning has a linkage to changes in perception about own performance, sense of ability, and workload. Thus, these variables may mediate the underlying mechanism of performance and motor learning differences between EXF and INF.

Understanding the effects of attentional focus instructions on perception and cognition may also help explain another variable that influences the attentional focus effects. Literature has shown that the effects of attentional focus may be sensitive to task difficulty. For example, research has shown that there was no difference between EXF and INF when performing an easy task but the EXF benefits over an INF were evident when performing a difficult task (Becker & Smith, 2013; Landers et al., 2005; Wulf et al., 2007). Currently, no modifications to existing theories have been provided to explain how task difficulty influenced the effects of attentional focus. However, considering the changes in mental workload and perceived competence by varying task difficulty, these parameters may explain how attentional focus effects change by varying task difficulty.

To develop the understanding of attentional focus from the cognitive views, the present study examined the effects of attentional focus instructions on explicit knowledge, mental workload, and perceived competence while participants practiced three task difficulties of a Fitts' reciprocal tapping task. Previously, explicit knowledge was assessed by counting the amount of explicit knowledge (Koudejiker et al., 2007; Poolton et al., 2006), categorized only into dichotomous categories of explicit knowledge (Poolton et al., 2006), or qualitatively examining the proportion of thoughts (Perreault & French, 2015). The present study extended the knowledge from the previous studies by assessing both the amount and types of different explicit knowledge. Additionally, to develop the knowledge of descriptive information, we adopted inferential statistics on the types of explicit knowledge, which was adapted in the previous study (Diekfuss & Raisbeck, 2016). Further, compliance checks have been adopted for the confirmation purposes of the assigned instruction to participants (Marchant et al., 2009; Stoate & Wulf, 2011). However, the magnitude of compliance may be different depending upon a given instruction (Lohse et al., 2014; Raisbeck et al., 2018). Thus, the present study also examined the magnitude of compliance. We hypothesized that mental workload would increase with an increase in task difficulty but decrease with practice. Further, the EXF group would lead to a lower mental workload score than the INF and CON groups. Similarly, the perceived competence would increase with time but would be lower in the easier task than when performing a more difficult task. Additionally, the EXF group would have a higher competence than the INF group. For explicit knowledge, the amount of explicit knowledge would increase with time due to the accumulation of knowledge, but the INF group would have a greater amount of explicit knowledge relative to the EXF and CON. Additionally, the INF group would have more self-monitoring thoughts (self-invoking trigger).

Methods

Participants

Sixty healthy young adults aged between 18 and 50 years (*M* = 22.21yrs., *SD* = .67 for males, *M* = 23.46 yrs., *SD* = .81 for females) were recruited to participate in this study. Participation was voluntary with no monetary incentives. Participants were free from upper extremity injuries, surgery, or pain at least in the last six months, and naive to the task. The institutional review board approved the study prior to the start of the study and participants completed an informed consent. Hand dominance was determined with the Edinburgh Handedness Inventory-Short Form (Veale, 2014). Six participants (2 participants in the INF group, 1 participant in the EXF group, and 3 participants in the CON group) were determined as left-handed. The other 54 participants were right-handed.

Task and Apparatus

The task was a modified reciprocal Fitts' task (*e.g.*, Fitts, 1954; Raisbeck et al., 2019; Salmoni & Mcilwain, 1979; Sasangohar, MacKenzie, & Scott, 2009), which has been shown to be sensitive to attentional focus manipulations (Alorani, Glazebrook, Sibly, Singer, & Steven, 2019; Raisbeck et al., 2019 The task was performed on a table (69.85 x 76.45 cm), and required participants to tap back and forth between two horizontally aligned targets with a stylus (2 x 2 x 9 cm, width x length x height, respectively) during a 30-second trial (Figure 3.2). Targets (7 x 7 cm) vary in the proportion of the *hit area*, with the center marked with a crosshair (1x1cm) and *mishit area* (Figure 3.2). Knowledge of results specific to error hits was provided with an LED light that turned on when the stylus touched the mishit area. Task difficulty was calculated using the Index of Difficulty (ID), where ID = $\log_2$ (2D/W) (Fitts, 1954; Fitts & Peterson, 1964). D represents the distance and W represents the size (*i.e.*, width) of the targets. For the present study, W was calculated by the tolerance limit (*i.e.*, the remaining width after subtracting the width of the stylus). Thus, for the width of the stylus is 2 cm and target area width of 6cm, ID was calculated as $\log_2$ (2D/4 cm) (the width of the stylus subtracted from the width of the hit area). The present study used three different dimensions of the hit areas (6 x 6, 4 x 4, and 3 x 3 cm for easy, medium, and high difficulty, respectively) and three different distance between two targets (8 cm, 16 cm, and 32 cm for easy, medium, and high difficulty, respectively), which corresponds to ID of 2 (ID_{low}), 4 (ID_{med}), and 6 (ID_{high}).

To measure performance, reflective markers were attached to the stylus and tracked by a 3D motion capture system (Qualisys, Sweden), which recorded the number of correct hits. The data were collected at 100 Hz sampling frequency. Auditory signals were introduced for three time points as a ready, start, end signal. The ready signal was presented (50 ms duration). After 500 ms, the start signal (50 ms duration) was presented.

Each trial was 30 second, thus the end signal was presented after 3000 ms from the start signal. All data was processed with MATLAB software (Mathworks, MA).

A manipulation check was adapted from a previous study (Raisbeck et al., 2019). The questionnaire consisted of two questions. The first question asked, "*what was the given instruction?"* The investigator recorded the responses in verbatim, and it was coded as correct or incorrect. The second question asked, "*How much were you able to follow that instruction?*" in a 7-point Likert Scale, 1 = "*don't remember*", 2 = "*sometimes*", 3 = "*one third of the times*", 4 = "*a half of the times*", "5 = most of the time", "6 = *almost always*", and "7 = *always*". Corresponding phrases were marked below each number. Regardless of the response of the second question, zero was given if the response of the first question was not correct.

Perceived competence was adopted from a previous study (Conroy et al., 2005; Fredricks & Eccles, 2002; Frihka, et al., 2019). Participants were asked, "*how well do you think you will perform on the following task?*" The response was recorded as a 7-point Likert Scale, where 1 as "*very poorly*" and 7 as "*very well*".

Subjective mental workload was measured using a NASA-TLX (Hart & Staveland, 1988). The questionnaire consisted of six different questions asking physical load, mental load, effort, time pressure, frustration, and feeling of success. Participants responded to each item question from a range of 0 to 20. The score of each item was multiplied by five and divided by the number of items to represent the overall mental workload in 0 - 100.

The explicit knowledge was assessed by asking participants' thoughts, strategies, and methods during performance (Koedijeker, et al. 2007). Specifically, participants were asked, "*in addition to the given instruction on the white sheet, please report if there were any methods or techniques that you adopted, or any thoughts, even if it is not related to the task. You do not have to answer if you were not thinking about anything*." The responses were recorded in verbatim.

Procedure

The overview of the study design is summarized in Figure 3.2. At the beginning of the experiment, participants completed the Edinburgh Handedness Inventory-Short Form (Veale, 2014) to determine hand dominance and were asked to sit in a chair in front of a table and as close to the edge of the table to minimize the trunk motion. Then, participants were informed of the general procedure. Participants were told to hold the top part of a stylus from the side with three fingers (thumb, index, and middle fingers). They were told, "*the task is to move a stylus back and forth between two targets*," and "*the goal of the task is to tap the targets as many times as possible during a 30 second trial, but emphasizing accuracy*". The investigator informed participants to aim at the center of the target. A speed-accuracy tradeoff task requires restricting movement speed and measuring accuracy/error as a dependent variable or restricting accuracy and measuring speed as a dependent variable. In the present study, the maximum number of errors (*i.e.,* error limit) that participants can make was predetermined and used the number of taps as a primary dependent variable. For this reason, participants were asked to 1) wait for the start signal while holding the stylus on the right target, 2) begin the movements only after the start signal, 3) hit the targets with the stylus as perpendicular to the targets as possible, 4) continue to reciprocally move the stylus back and forth even if they made an error or missed tapping the target, and 5) perform additional trials if they made more errors than an error limit.

Prior to the baseline, participants received two 30-second trials with their dominant hand with ID of 3. During this phase, the emphasis was placed on understanding the general procedures. *A priori*, one additional trial was determined to provide if participants did not understand the procedure. All participants understood the procedure in two trials.

Following the familiarization phase, participants performed one 30-second baseline trial for three difficulties: ID_{low}, ID_{med}, and ID_{high} in the order of the low ID to high ID conditions. First, participants completed a perceived competence questionnaire before each ID trial, followed by one trial for each ID. The error limits for each ID were 2, 4, and 10 error taps for ID_{low}, ID_{med}, and ID_{high}, respectively. These error limits were predetermined from a pilot study (N = 11). Participants were reminded of the goal of the task and performed the trials with their *non-dominant hand*. The investigator counted the number of errors and reported to participants every after trial. A trial was recollected when participants made any movements prior to a start signal or exceeded the error limits. To maintain the number of trials relatively similar across participants, the maximum number of trials for each ID during the baseline was predetermined as three trials. If participants did not complete a trial below the error limit within three trials, that participant was excluded. None of the participants exceeded this predetermined limit of trials. After a trial in each ID, participants received the NASA-TLX. Following the performance baseline, verbal fluency baseline, as a part of familiarization of the transfer test, was completed. In this test, participants were asked to name as many animals as possible that begin with a letter, “A”, which was introduced between the ready and start signals during a 30-second trial (no physical performance). The responses were recorded, and the number of responses were counted. The compliance checks were not provided during the baseline since participants did not receive attentional focus instructions to follow.

Following the baseline, participants were randomly assigned to one of the EXF (n = 20), INF (n = 20), or control (CON, n = 20) groups. The goal of the task was reminded, and participants were informed of the importance of complying with the instructions that they would receive. Participants in the EXF group were told, “*mentally focus on moving the pen as fast and accurately as possible*”. The instruction for the INF group was, “*mentally focus on moving your hand as fast and accurately as possible*”, and the instruction for the CON group was, “*mentally focus only on doing your best”*. The instruction was provided in a piece of paper to distinguish it from other general procedures provided during the familiarization phase and verbally repeated prior to every trial. The acquisition phase consisted of four blocks of nine trials of three consecutive trials of ID_{low}, three trials of ID_{med}, and three trials of ID_{high}. Similar to the baseline, participants completed a perceived competence question before each ID, and then practiced three trials. After the trials, participants completed the NASA-TLX, compliance check, and explicit knowledge questionnaires. On Day 1, participants performed two blocks, with the order from the low to high ID conditions in Block 1, but the order of difficulty was randomized for Block 2. On Day 2 (48 hours later), participants revisited the lab and completed two additional blocks (a total of 18 trials) with the order of practice randomized. Throughout the experiment, the same error limits (2, 4, and 10 for ID_{low}, ID_{med}, and ID_{high}, respectively) were used. For each ID, participants completed at least two trials below the error limit. That is, if two trials exceeded the error limit within the first three trials, additional trials were collected until the second trial below the error limit was collected. The maximum number of total trials for each ID in each block was determined *a priori* as five trials. None of the participants exceeded five trials.

Following the acquisition phase, participants completed a 5-minute delayed retention test with the same assigned instructions during the acquisition phase. Participants completed a perceived competence questionnaire, and then performed one trial for each ID from lower to higher ID conditions. After the trial for each ID, participants were asked to complete the NASA-TLX, compliance checks, and explicit knowledge questionnaires. On Day 3, participants completed a 48-hour retention test with the same procedure of the 5-minute retention test. Following the 48-hour retention, participants completed a dual task transfer test. Participants were asked to perform the task while naming as many animals as possible starting with a given alphabet letter. Participants performed one trial low, medium, and high ID condition with C, P, and G, respectively. The questionnaire procedure was also the same as the baseline and retention tests. All participants completed the experiment on either Monday/Wednesday/Friday or Tuesday/Thursday/Saturday schedule.

Data Analysis

Performance data before and after the start and end signals was eliminated, missing data were interpolated with spline interpolation function of MATLAB, and these data were filtered using a Savitzky-Golay (SG) filter (r = 1, m = 9). The parameters were determined from pilot data by qualitatively examining the residual plot, assessing normality, and superimposing the raw data over the filtered data. The center of the targets was determined from 5s static trials. The spatial accuracy of measurement was also determined by a 5s static trial, and this was 0.02 mm SD in the x, y, and z axis from one of the markers. The instant of taps was determined in the following manner. First, a top right reflective marker in the z-axis (vertical plane) was identified. Then, the ranges approximately the bottom of the marker in each stroke were identified. Finally, the lowest point within each range was determined as the instant of hit. Performance was measured as Movement Time (MT) and calculated as the number of taps divided by 30 (seconds). Perceived competence was measured in 7-point Likert scale. Each item of the NASA-TLX (0-20) was multiplied by five and divided by the number of items to represent the overall mental workload from 0 - 100. For the compliance and explicit knowledge questions, the response of the first question ("what was the given instruction?") was assessed as correct or incorrect. The second question (the magnitude of the compliance to the given instruction) was responded by a 7-point Likert Scale. Regardless of the response of the second question, zero was given if the response of the first question was incorrect. The third question (different thoughts in addition to the given instruction) was used to assess explicit knowledge. For explicit knowledge, two different methods were used. First, the number of responses (thoughts) were counted and used for analysis as a continuous variable, which was used in the previous studies Koedijker et al., 2007; Poolton et al., 2006). Second, the responses were categorized inductively (Berniers et al., 2011; 2016; Riasbeck et al., 2018; Yamada et al., 2020). The categorization resulted into five categories: “Nothing”, “Techniques (strategies)”, “Self-reflection (attention regulation, thoughts, self-reflection, emotion)”, “sensation (physiological fatigue)”, and “Task-Irrelevant thoughts”. The response was categorized as “nothing” when there was no response or participants were not thinking about anything except the given instruction. “Techniques” were categorized when the response was regarding strategies or themes that participants had during trials, such as “*I was focusing more on accuracy*,” “*the height or trajectory of the stylus*,” and “*slow down*,” “*keeping the pen straight up*”. The responses were categorized into “Self-reflection” for comments about thoughts and affective responses that participants were *aware* of during performance, including frustration, internal thoughts, retrospection, attention regulation. Examples from the results were “it’s *hard* to hit the target”, “*felt like* the target was getting smaller”, “I was getting *stressed”*, “*talking myself to stay on the task*”, and “*I was mentally fatigued*”. The category of “Self-reflection” can be considered as self-monitoring thoughts, which may provoke micro-choking (Perreault & French, 2015). “Sensations” were responses specific to physiological sensations (*e.g.,* physical fatigue, pain). The task-irrelevant thoughts were any description that was not related to the task, such as “*I was thinking about my work*”. For the categories of explicit knowledge, all responses were aggregated and assessed to see the general influence of given instructions. For statistics, continuous variable data (*i.e.*, NASA-TLX, competence, compliance, the amount of explicit knowledge) were analyzed using SPSS (IBM, version 26) and categorical data (*i.e.*, type of explicit knowledge) were analyzed using Excel (Microsoft Office).

Statistical Analysis

Baseline for the NASA-TLX and perceived competence were measured with a 3 (Group) x 3 (ID) ANOVA with repeated measures on the second factor. For practice, the NASA-TLX, perceived competence, and the amount of explicit knowledge were measured using a 3 (Group) x 3 (ID) x 4 (Block) ANOVA with repeated measures on the last two factors. To measure the learning effects, a 3 (Group) x 3 (ID) x 3 (Time: Baseline, 5-min retention, 48-hour retention) ANOVA with repeated measures on the last two factors was used. The effect of the dual task during the transfer test was measured using a 3 (Group) x 3 (ID) ANOVA with repeated measures on the second factor. Performance data were measured elsewhere (Dissertation manuscript 1). Alpha was set at .05 *a priori* for all analyses. *Post hoc* tests were conducted, if necessary, with Bonferroni correction at alpha level of .05. When there was a violation of sphericity in the main analyses, a Greenhouse-Geiser correction was used to interpret the results. To measure the categories of explicit knowledge, a chi-square test of independence was conducted. For *post hoc* tests of the chi-square test, the adjusted residuals were used (Sharpe, 2015) after adjusting the *p*-value with a Bonferroni correction (*i.e.*, 15 tests ‘3 groups x 5 categories’; $p = 0.003$ with critical value of – 2.713). The effect sizes were qualitatively interpreted, using a partial eta squared (η^2_p), with η^2_p = .011 to .05 as small, .06 to .13 as medium, and > .14 as large effect size (Cohen, 1988). The magnitude of compliance check was measured using 3 (Group) x 3 (ID) x 4 (Blocks) ANOVA during practice and 3 (Group) x 3 (ID) x 3 (Time) during testing phases with repeated measures on the last two factors.

Results

Performance

The results of the performance in MT and the number of error taps have been discussed elsewhere (see Figure 4.1 and 4.3 in Chapter IV). In brief, the comparison between blocks of the acquisition phase showed that MT significantly improved from Block 1 relative to Block 2, 3, and 4 (as well as Block 2 relative to Block 3 and 4). MT in the ID_{low} was significantly faster than the ID_{med} and ID_{high} conditions. No group difference was evident. For error taps, the number of error taps were higher in the ID_{high} condition than the lower ID conditions. However, there was no significant improvements between blocks. For the testing phase (Baseline, 5-minute and 48-hour retention tests), MT was faster, and the number of error taps were lower in the retention tests than the baseline. MT and error taps in the ID_{low} were significantly better than the ID_{med} and ID_{high} conditions. Further, group differences were not evident, however there was an interaction effect of time by ID for MT, suggesting that the magnitude of improvement was lower in the ID_{med} condition. In the transfer test, there was no difference in MT between group; however, the INF group of error taps were trending to be different relative to the CON group.

Mental Workload

Baseline

There was no group difference ($F_{2,57} = .24$, $p > .05$, $\eta^2_p < .01$). There was a significant difference between the ID conditions ($F_{1.40, 79.68} = 89.89$, $p < .01$, $\eta^2_p = .61$). *Post hoc* tests confirmed that mental workload was higher in the ID_{high} condition than ID_{med} condition ($p < .01$) and the ID_{med} condition was higher than the ID_{low} condition ($p < .01$) (Figure 6.1). The Mean and SD of the dependent variables are summarized in Table 6.1. All the F- and p-values, and partial eta squared of the dependent variables are summarized in Appendix O.

Practice phase

Significant differences were found in ID ($F_{1.24, 70.77} = 95.87$, $p < .01$, $\eta^2_p = .63$) and time ($F_{2.17, 123.68} = 40.56$, $p < .01$, $\eta^2_p = .42$). All other results were not different ($p > .05$). *Post hoc* tests for ID showed that the mental workload was higher in the ID_{high} condition than the ID_{med} condition ($p < .01$) and the ID_{med} was higher than the ID_{low} condition ($p <. 01$), but it decreased with practice: Block 1 was higher than Block 2, 3, and 4 ($p < .01$), Block 2 was higher than Block 3 and 4 ($p < .01$), where no difference was found between Block 3 and 4 ($p > .05$).

Testing phase

Similar to the practice phase, there were significant differences in ID ($F_{2,114} = 100.54$, $p < .01$, $\eta^2_p = .64$) and time ($F_{1,57} = 13.68$, $p < .01$, $\eta^2_p = .19$). There were no differences in other factors. *Post hoc* test for ID showed that mental workload was higher in the ID_{high} than the ID_{med} ($p < .01$) and the ID_{med} condition than the ID_{low} condition ($p <.$

01). Further, mental workload continued to decrease from the 5-min retention test to 48-hour retention test. During the transfer test, however, none of the factors were found to be significant.

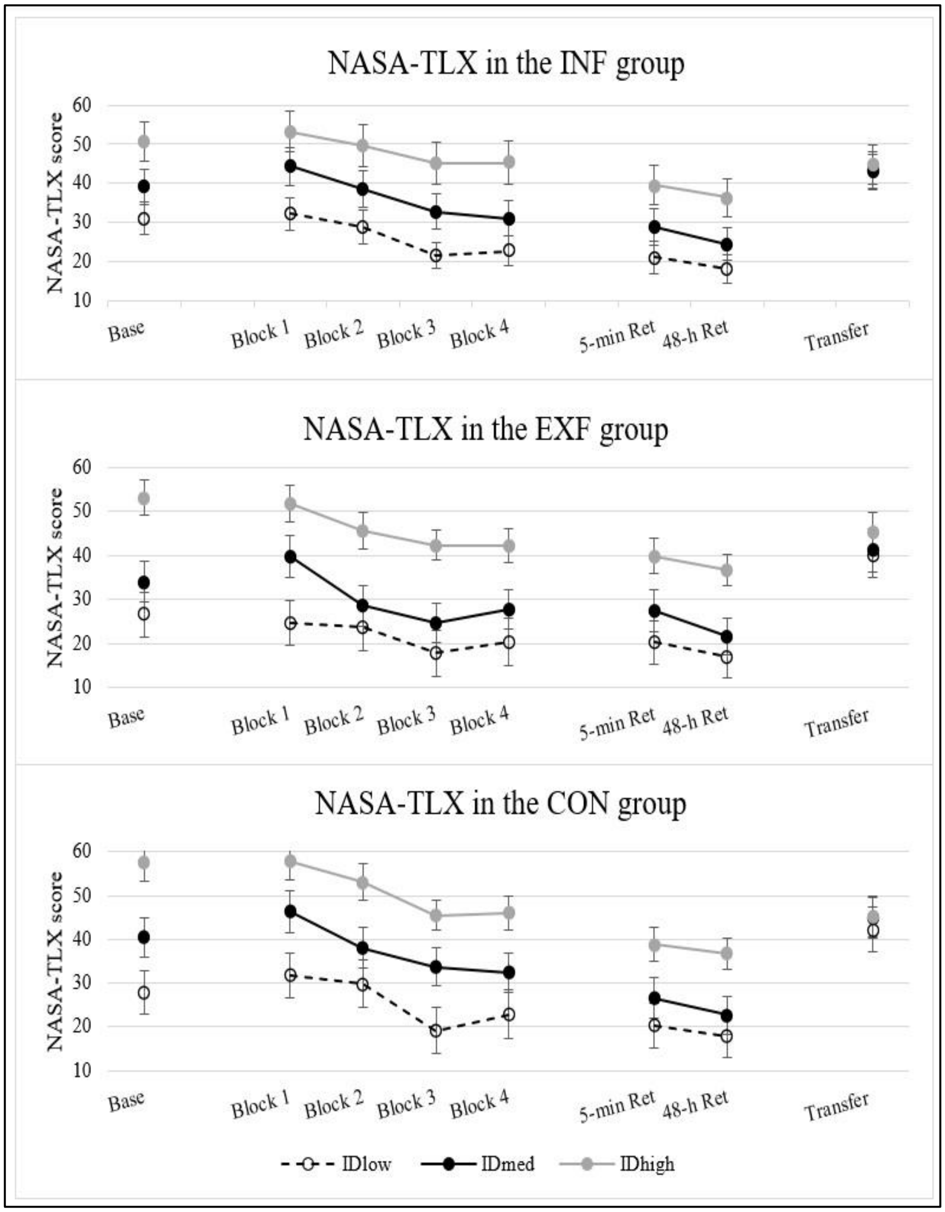


Figure 6.1. NASA-TLX of ID Conditions by Group. Bars are within factor of SEM.

Table 6.1. Mean (SD) of the NASA-TLX Scores

		Base	Block 1	Block 2	Block 3	Block 4	5-min Ret	48-h Ret	Transfer
INF	ID low	31.04 (15.74)	32.17 (19.31)	28.83 (22.46)	21.50 (16.27)	22.71 (19.21)	21.00 (18.78)	18.00 (17.98)	43.08 (21.24)
	ID med	39.04 (20.21)	44.33 (22.15)	38.58 (22.93)	32.79 (21.45)	30.96 (20.76)	28.71 (23.07)	24.38 (21.94)	43.33 (22.91)
	ID high	50.58 (22.34)	53.21 (20.96)	49.63 (21.45)	45.13 (24.70)	45.25 (22.63)	39.46 (22.75)	36.38 (23.92)	44.71 (22.01)
EXF	ID low	26.50 (19.37)	24.71 (20.08)	23.67 (17.09)	17.79 (14.66)	20.25 (16.61)	20.17 (20.18)	17.00 (14.73)	40.00 (17.83)
	ID med	34.00 (20.59)	39.83 (20.63)	28.54 (19.72)	24.67 (17.19)	27.63 (19.63)	27.46 (21.72)	21.63 (18.03)	41.08 (19.29)
	ID high	53.17 (21.67)	51.79 (23.15)	45.54 (26.47)	42.33 (22.58)	42.21 (24.20)	39.83 (25.00)	36.63 (19.19)	45.38 (21.80)
CON	ID low	27.88 (18.74)	31.83 (16.99)	29.79 (16.22)	19.04 (14.69)	22.88 (16.23)	20.33 (14.44)	17.63 (14.42)	42.21 (20.78)
	ID med	40.33 (20.12)	46.29 (22.31)	38.04 (18.51)	33.71 (20.71)	32.42 (19.29)	26.54 (17.46)	22.58 (16.40)	45.04 (23.56)
	ID high	57.42 (21.67)	57.92 (24.81)	53.08 (25.36)	45.42 (23.10)	46.08 (26.46)	38.88 (19.97)	36.71 (21.06)	45.13 (24.87)

Note. Base = Baseline; 5-min Ret = 5-minute retention test; 48-h Ret = 48-hour retention test; transfer = transfer test.

Explicit Knowledge

Amount of explicit knowledge

Practice phase. Significance effects were found in ID ($F_{2,114}$ = 7.78, p <. 01, η^2_p = .12) and time ($F_{3,171}$ = 17.19, p < .01, η^2_p = .23) (Figure 6.2). *Post hoc* tests for ID showed that there was no difference in the amount of explicit knowledge between the ID_{low} and the ID_{med} conditions (p > .05), but the amount of explicit knowledge was larger in the ID_{high} condition than the low condition (p < .01). For the time factor, *post hoc* tests showed that explicit knowledge was higher in Block 1 than Block 2, 3, and 4 (all p < .01), where other blocks were non-significant. The mean and SD of the amount of explicit knowledge score are summarized in Table 6.2.

Testing phase. There was a significant effect in ID ($F_{1.69,\, 96.00} = 13.75$, $p < .01$, $\eta^2_p = .19$). However, there was an interaction effect of ID by group ($F_{3.37,\, 96.00} = 2.83$, $p < .05$, $\eta^2_p = .09$). *Post hoc* tests of a repeated measure of ANOVA between time factor in each group showed that the EXF showed a significant difference in ID ($F_{2,38} = 25.93$, $p <. 01$, $\eta^2_p = .58$), whereas the INF and CON did not show any differences in time and interaction ($p > .05$). Specifically, only for the EXF group, the amount of explicit knowledge was higher in the ID_{high} condition than the ID_{med} condition ($p <. 01$) and the ID_{low} ($p <. 01$), and the ID_{med} condition was higher than the ID_{low} condition ($p < .05$). In the transfer test, a significance was found in ID ($F_{2,114} = 3.36$, $p < .05$, $\eta^2_p = .06$). *Post hoc* tests just failed to reach a significance between the ID_{low} ($M = 1.13$, $SD = .34$) and the ID_{high} ($M = 1.28$, $SD = .49$) condition ($p = .054$), but it suggests that the source significance in the time factor in the main analysis is the difference between these two conditions.

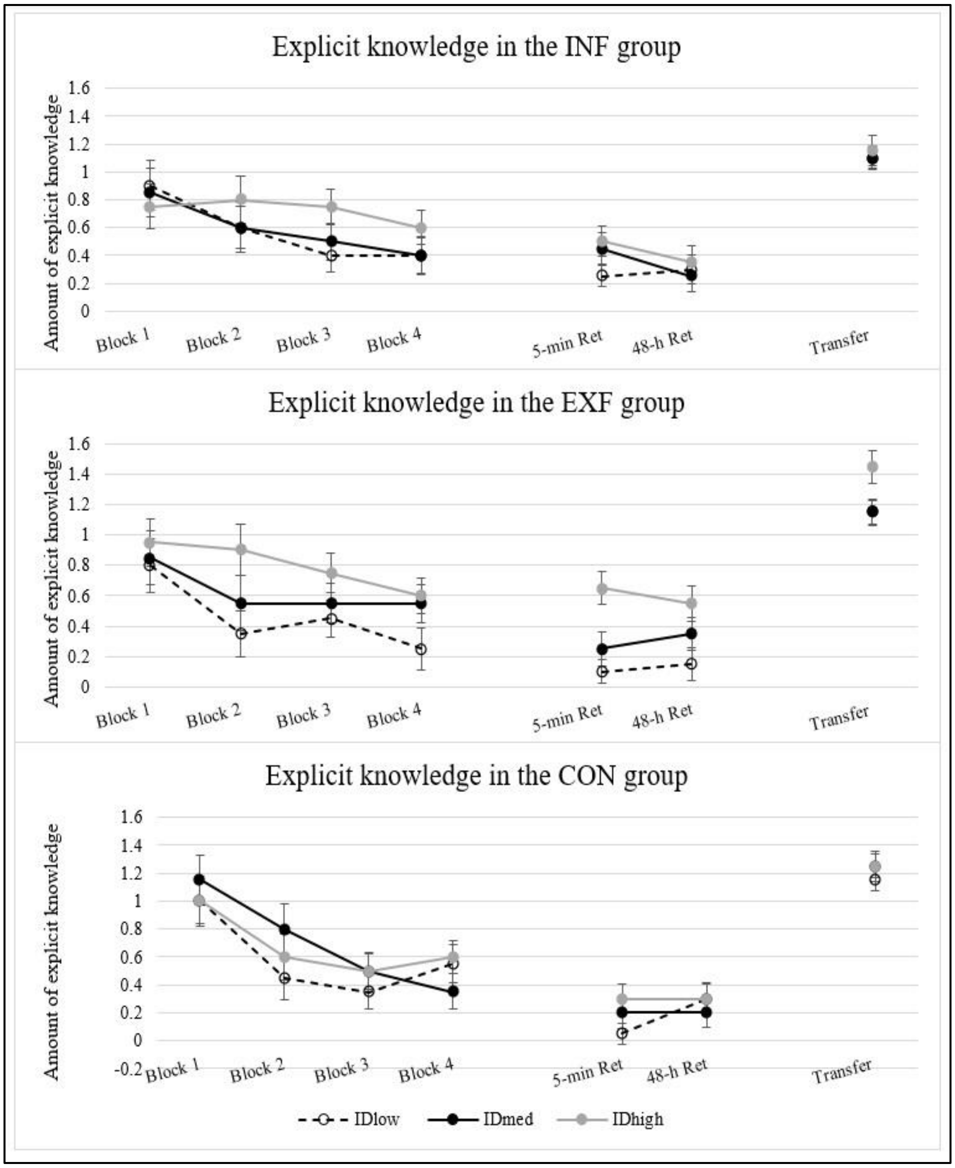


Figure 6.2. The Amount of Explicit Knowledge of ID Conditions by Group. Bars are SEM of the within factor.

Table 6.2 Mean (SD) of the Amount of Explicit Knowledge

		Block 1	Block 2	Block 3	Block 4	5-min Ret	48-h Ret	Transfer
INF	ID low	0.90 (.79)	0.60 (.89)	0.40 (.60)	0.40 (.75)	0.25 (.44)	0.30 (.57)	1.10 (.31)
	ID med	0.85 (.88)	0.60 (.88)	0.50 (.61)	0.40 (.50)	0.45 (.60)	0.25 (.55)	1.10 (.31)
	ID high	0.75 (.91)	0.80 (.77)	0.75 (.64)	0.60 (.60)	0.50 (.51)	0.35 (.59)	1.15 (.37)
EXF	ID low	0.80 (.70)	0.35 (.49)	0.45 (.51)	0.25 (.44)	0.10 (.31)	0.15 (.37)	1.15 (.37)
	ID med	0.85 (.59)	0.55 (.60)	0.55 (.60)	0.55 (.51)	0.25 (.44)	0.35 (.49)	1.15 (.37)
	ID high	0.95 (.51)	0.90 (.45)	0.75 (.61)	0.60 (.50)	0.65 (.49)	0.55 (.51)	1.45 (.44)
CON	ID low	1.00 (.92)	0.45 (.60)	0.35 (.49)	0.55 (.60)	0.05 (.22)	0.30 (.47)	1.15 (.37)
	ID med	1.15 (.88)	0.80 (.90)	0.50 (.51)	0.35 (.67)	0.20 (.41)	0.20 (.41)	1.25 (.44)
	ID high	1.00 (.71)	0.60 (.94)	0.50 (.61)	0.60 (.53)	0.30 (.47)	0.30 (.53)	1.25 (.44)

Types of explicit knowledge

Overall, 389 thoughts were identified for the INF group, 356 thoughts were identified for the EXF group, and 385 thoughts were identified for the CON group (Table 6.3). For the INF group, 52.44% were nothing, 25.45% were techniques, 14.65% were self-reflection, 5.91% were irrelevant, and 1.54% were sensations. For the EXF group, 47.47% were nothing, 36.52% were techniques, 7.02% were self-reflection, 7.02% were irrelevant, and 1.97% were sensations. For the CON group, 50.39% were nothing, 31.69% were techniques, 14.29% were self-reflection, 3.12% were irrelevant, and 0.52% were sensations. The chi-square test showed that the proportion of the categories were significantly different, (X^2 8, N = 60) = 28.34. *Post hoc* test with adjusted residuals with a critical value of ± 2.71305 based on the number of tests (3 groups x 5 categories = 15, which resulted in adjusted *p*-value of .0033) showed that explicit knowledge about techniques were significantly lower than expected value for the INF group (adjusted residuals = - 2.967). In contrast, for the EXF group, explicit knowledge about techniques were significantly higher (adjusted residuals = 2.74) and explicit knowledge about self-reflection were lower than the expected values (adjusted residuals = - 3.57).

Table 6.3. Categories of Explicit Knowledge

	Observed counts (Proportions within each group in %)					
	Nothing	Technique	Emotion	Irrelevant	Sensation	Row Sum
INF	204 (52.44)	99 (25.45)	57 (14.65)	23 (5.91)	6 (1.54)	389 (100)
EXF	169 (47.47)	130 (36.52)	25 (7.02)	25 (7.02)	7 (1.97)	356 (100)
CON	194 (50.39)	122 (31.69)	55 (14.29)	12 (3.12)	2 (0.52)	385 (100)
Col Sum	567	351	137	60	15	Total 1130

	Adjusted residuals				
	Nothing	Technique	Emotion	Irrelevant	Sensation
INF	1.13	-2.97*	1.84	0.65	0.45
EXF	-1.28	2.74ǂ	-3.53*	1.77	1.28
CON	0.11	0.33	1.56	-2.35	-1.69

Note. The upper table shows the raw counts of categorized EK and its proportion. Row Sum = Sum of the raw row counts; Col Sum = Sum of the raw column counts; Proportion indicates percentage within each group. The bottom table shows the *post hoc* test results using adjusted residuals, examining whether each category of thoughts is higher or lower than expected values; * indicates the observed value was significantly lower than the expected value at .05; ǂ indicates the observed value was significantly higher than the expected value at .05.

Perceived Competence

Baseline

There was a significant difference in ID ($F_{1.72, 98.00} = 25.46$, $p <. 01$, $\eta^2_p = .31$) with no difference in group or interaction. *Post hoc* tests for ID confirmed that the ID_{high} condition showed the lowest competence compared to the ID_{low} condition ($p <. 01$), whereas no difference was found between the ID_{low} and ID_{med} conditions ($p > .05$). Figure 6.3 shows the mean and SE of perceived competence over different time periods. The mean scores and SD of the perceived competence score are summarized in Table 6.4.

Practice phase

There were significant differences in ID ($F_{1.75, 99.01} = 413.33$, $p < .01$, $\eta^2_p = .88$) and time ($F_{2.50, 142.35} = 39.78$, $p < .01$, $\eta^2_p = .41$). *Post hoc* tests for ID showed the ID_{low} condition was significantly lower than the ID_{med} condition ($p < .01$) and the ID_{med} condition was significantly lower than the ID_{high} condition ($p < .01$). *Post hoc* tests for time factor showed a gradual increase in perceived competence from Block 1 to Block 2 ($p < .01$), Block 2 to Block 3 ($p < .01$), but the score leveled off after this phase (no difference between Block 3 and 4, $p >.05$).

Testing phase

A significant difference was found in ID ($F_{1.60,91.30} = 275.35$, $p < .01$, $\eta^2_p = .83$). *Post hoc* tests revealed that the competence score was higher for the ID_{low} condition than the ID_{med} condition ($p <. 01$) and the ID_{med} condition was higher than the ID_{high} condition ($p <. 01$). No other difference was found. During the transfer test, there was a significant effect only in ID ($F_{1.71, 97.60} = 85.29$, $p < .01$, $\eta^2_p = .60$). *Post hoc* tests showed that the competence score was higher in the ID_{low} than ID_{med} condition ($p < .01$) and the ID_{med} condition was higher than the ID_{high} condition ($p < .01$).

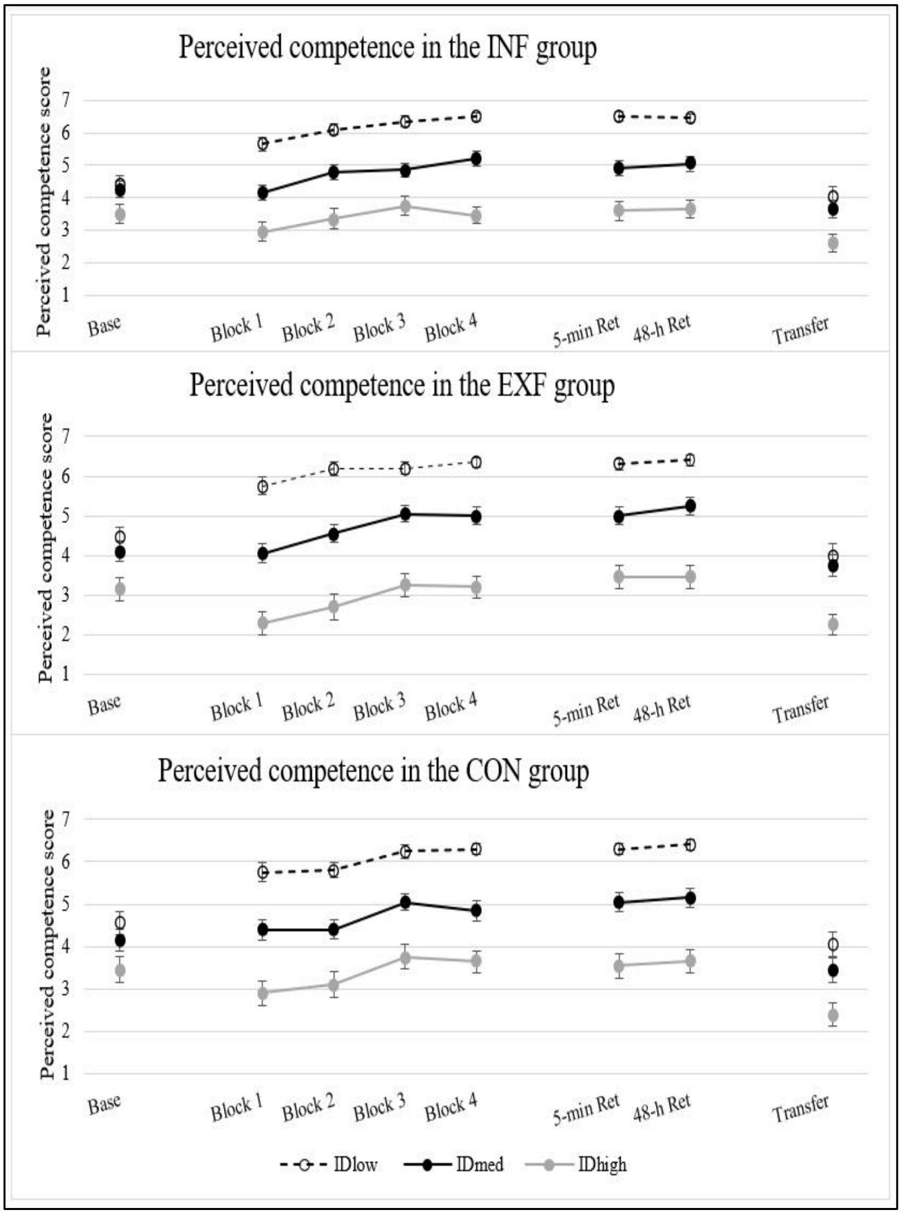


Figure 6.3. Perceived Competence of ID Conditions by Group. Bars are SEM of the within factor.

Table 6.4 Mean (SD) of Perceived Competence

		Base	Block 1	Block 2	Block 3	Block 4	5-min Ret	48-h Ret	Transfer
INF	ID low	4.40 (1.05)	5.65 (1.23)	6.10 (.72)	6.35 (.67)	6.50 (.51)	6.50 (.61)	6.45 (.60)	4.05 (1.32)
	ID med	4.25 (1.07)	4.15 (1.14)	4.80 (.89)	4.85 (.88)	5.20 (1.01)	4.90 (.97)	5.05 (1.05)	3.65 (1.27)
	ID high	3.50 (1.47)	2.95 (1.36)	3.35 (1.35)	3.75 (1.02)	3.45 (1.00)	3.60 (1.05)	3.65 (1.31)	2.60 (1.19)
EXF	ID low	4.45 (1.28)	5.75 (.72)	6.20 (.70)	6.20 (.70)	6.35 (.59)	6.30 (.66)	6.40 (.60)	4.00 (1.26)
	ID med	4.10 (1.29)	4.05 (1.28)	4.55 (.94)	5.05 (.94)	5.00 (1.12)	5.00 (.97)	5.25 (.91)	3.75 (1.16)
	ID high	3.15 (1.18)	2.30 (1.22)	2.70 (1.34)	3.25 (1.48)	3.20 (1.24)	3.45 (.91)	3.45 (1.19)	2.25 (1.02)
CON	ID low	4.55 (1.23)	5.75 (.96)	5.80 (.89)	6.25 (.78)	6.30 (.57)	6.30 (.47)	6.40 (.60)	4.05 (1.39)
	ID med	4.15 (.99)	4.40 (.75)	4.40 (1.23)	5.05 (.87)	4.85 (1.04)	5.05 (1.10)	5.15 (1.04)	3.45 (1.40)
	ID high	3.37 (1.33)	2.90 (1.37)	3.10 (1.48)	3.75 (1.33)	3.65 (1.16)	3.55 (1.40)	3.65 (1.28)	2.40 (1.20)

Note. Base = Baseline; 5-min Ret = 5-minute retention test; 48-h Ret = 48-hour retention test; transfer = transfer test.

Compliance

Practice phase

There were main effects in ID ($F_{1.56,\ 88.81}$ = 58.84, p < .01, η^2_p = .51), time ($F_{2.11,\ 128.18}$ = 12.65, p < .01, η^2_p = .18), group ($F_{2,57}$ = 8.32, p <. 01, η^2_p = .23). However, interaction effects of ID by group ($F_{3.21,\ 88.8}$1 = 3.92, p < .05, η^2_p = .12) and ID by time ($F_{3.62,\ 206.45}$ = 3.45, p < .05, η^2_p = .06) were found (Figure 6.4). *Post hoc* tests on ID by group revealed that at the ID_{low} and ID_{med} conditions, the compliance score of the INF was significantly lower than the CON (p < .05 for both ID conditions) with no difference between the EXF and CON and EXF and INF (p > .05 for both ID conditions). In the ID_{high} condition, both EXF (p < .01) and INF (p < .05) groups showed lower scores than the CON group with no significant difference between the EXF and INF groups in all ID's. The difference was also found in the relationship between ID's. In the EXF and INF groups, the magnitude of compliance was higher in the ID_{low} condition compared to the ID_{med} condition ($p <. 01$) and the compliance during the medium ID was higher than the ID_{high} condition ($p <. 01$). However, in the CON group, the magnitude of compliance was higher in the ID_{low} condition than two higher ID conditions ($p < .01$), but the ID_{med} and ID_{high} conditions were not different ($p > .05$). *Post hoc* tests of the interaction of ID by time showed that there was no difference in the magnitude of compliance between ID's in Block 1 (all $p > .05$). However, from Block 2 to 4, there was a significant distinction in the score: the ID_{low} was higher than the ID_{med} condition, and the ID_{med} was higher than the ID_{high} condition ($p < .01$ for all conditions). The mean and SD of the magnitude of compliance score are summarized in Table 6.5.

Testing phase

In the retention tests, there were significant effects in ID ($F_{1.62,92.59} = 49.89$, $p < .01$, $\eta^2_p = .47$) and interaction of ID by group ($F_{3.25,92.59} = 5.05$, $p < .01$, $\eta^2_p = .15$). A three-way interaction between group, ID, and time was also found ($F_{4,114} = 2.60$, $p < .05$, $\eta^2_p = .08$). Therefore, *post hoc* tests of 3 (ID) x 2 (Time) ANOVA with repeated measures on both factors were conducted for each group. The results for the INF group showed a significant effect in ID ($F_{1.55,29.42} = 24.07$, $p < .01$, $\eta^2_p = .56$) with all other factors non-significant ($p > .05$). For the EXF group, a significance was found in ID ($F_{1,38} = 24.64$, $p < .01$, $\eta^2_p = .57$). Although a significance was not reached, there was a large effect size in time ($F_{1,19} = 4.21$, $p = .053$, $\eta^2_p = .18$), suggesting that no changes in the INF between the

5-minute and 48-hour retention tests but the EXF was tending to further increase the compliance from the 5-minute to 48-hour retention tests. This effect was again different in the CON group. There was a significant effect in ID ($F_{2,38} = 4.02$, $p < .05$, $\eta^2_p = .18$) as shown in other two groups; however, the CON group also showed a non-significant, but a trending interaction of ID by time ($F_{2,38} = 3.17$, $p = .053$, $\eta^2_p = .14$), indicating that the compliance during the ID_{high} condition in the 48-hour retention test was lower than the ID_{low} condition while this difference was not evident in the 5-minute retention test. This was confirmed by separately analyzing the ID factor at the 5-minute retention ($p > .05$) and 48-hour retention test ($F_{1.51,28.68} = 6.21$, $p <. 01$, $\eta^2_p = .25$; between the ID_{low} and ID_{high}, $p < .05$; between the ID_{low} and ID_{med}, $p > .05$; between the ID_{med} and ID_{high}, $p > .05$).

In the transfer test, significant differences were found in ID ($F_{1.81,103.32} = 7.72$, $p <. 01$, $\eta^2_p = .12$) and interaction of ID by group ($F_{3.63,103.32} = 3.35$, $p <. 05$, $\eta^2_p = .11$). *Post hoc* tests were conducted for the interaction effect and showed that the compliance was lower in the ID_{low} condition relative to the ID_{high} condition ($p < .05$) in the INF group. For the EXF group, not only the difference between the ID_{low} and ID_{high} conditions ($p < .01$), the compliance in the ID_{high} condition was also lower than the ID_{med} condition (p < .05), where no difference was found between the ID_{med} and ID_{high} conditions. These ID differences were not evident in the CON group.

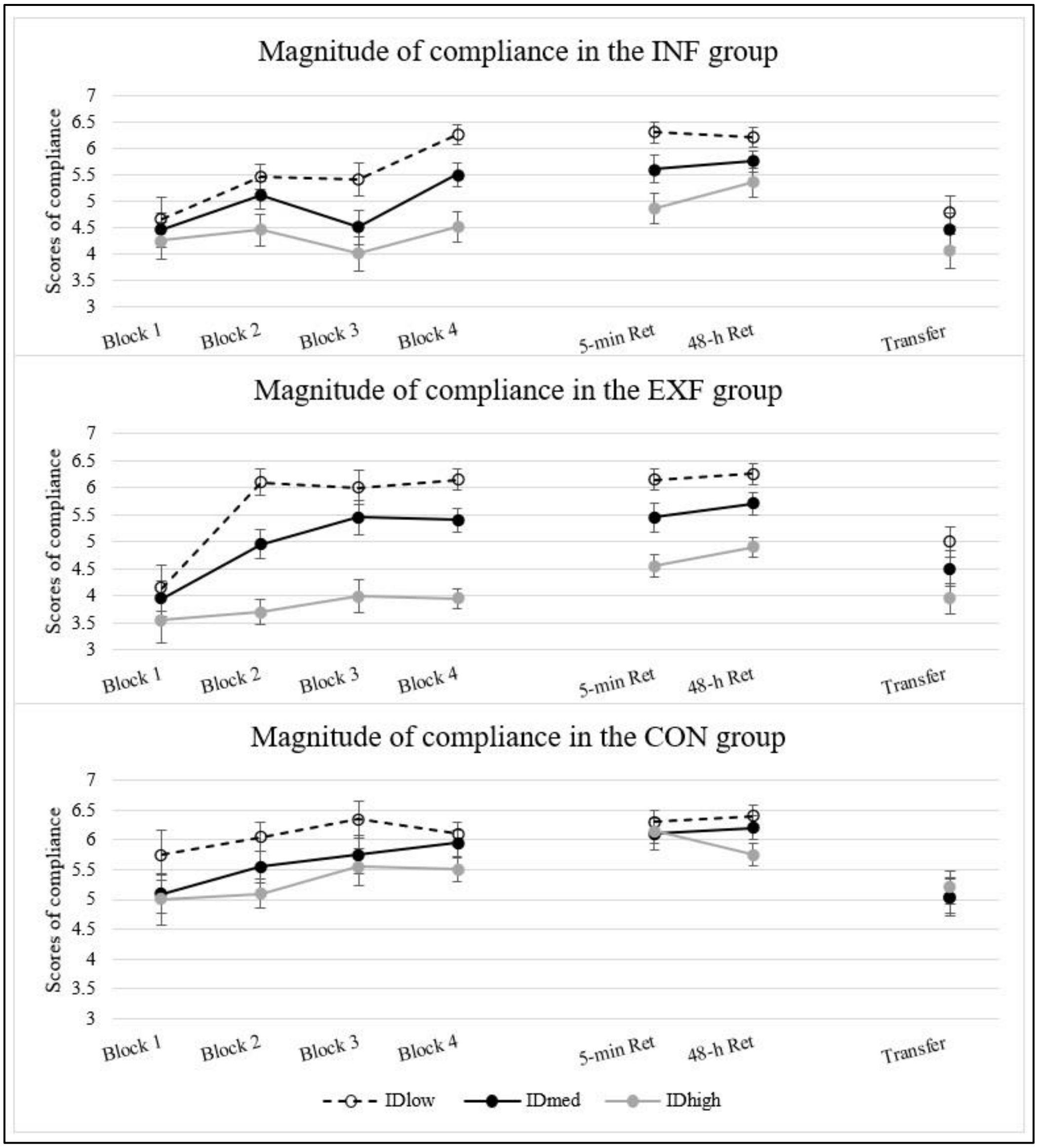


Figure 6.4. Magnitude of Compliance of ID Conditions by Group

Table 6.5 Mean (SD) of the Magnitude of Compliance

		Block 1	Block 2	Block 3	Block 4	5-min Ret	48-h Ret	Transfer
INF	ID low	4.65 (2.18)	5.45 (1.32)	5.40 (2.06)	6.25 (1.07)	6.30 (.98)	6.20 (.89)	4.80 (1.20)
	ID med	4.45 (1.50)	5.10 (1.12)	4.50 (1.91)	5.50 (.95)	5.60 (1.39)	5.75 (.97)	4.45 (1.25)
	ID high	4.25 (1.59)	4.45 (1.05)	4.00 (1.72)	4.50 (1.19)	4.85 (1.63)	5.35 (1.23)	4.05 (1.43)
EXF	ID low	4.15 (2.28)	6.10 (.79)	6.00 (.86)	6.15 (.75)	6.15 (.93)	6.25 (.85)	5.00 (1.17)
	ID med	3.95 (1.43)	4.95 (1.19)	5.45 (1.05)	5.40 (.99)	5.45 (1.23)	5.70 (.86)	4.50 (1.32)
	ID high	3.55 (1.32)	3.70 (1.49)	4.00 (1.34)	3.95 (1.32)	4.55 (1.32)	4.90 (1.23)	3.95 (1.50)
CON	ID low	5.75 (.85)	6.05 (1.00)	6.35 (.88)	6.10 (.72)	6.30 (.80)	6.40 (.82)	5.05 (1.43)
	ID med	5.10 (1.37)	5.55 (1.28)	5.75 (1.16)	5.95 (.99)	6.10 (.91)	6.20 (.86)	5.05 (1.61)
	ID high	5.00 (1.75)	5.10 (1.52)	5.55 (1.19)	5.50 (1.36)	6.15 (.81)	5.75 (1.24)	5.20 (1.36)

Discussion

The present study examined the effects of attentional focus instructions on mental workload, perceived competence, and explicit knowledge when participants practiced an aiming task that varies three difficulty levels. We hypothesized that mental workload would be higher in the higher ID's, mental workload would decrease as practice progressed, and the EXF group would lead to a lower mental workload score than the INF group. For the perceived competence, we hypothesized that the competence score would increase with time and it would be higher for the lower ID’s, but the EXF group would have a higher score than the INF group. For explicit knowledge, it was hypothesized that the amount of explicit knowledge would increase with time due to the accumulation of knowledge, but the INF group would have a greater amount of explicit knowledge relative to the EXF and CON. Additionally, the INF group would have a greater proportion of self-monitoring thoughts than the EXF and CON groups.

Mental Workload

The effects of difficulty and learning

The hypotheses about time and ID were supported. All groups showed a similar pattern of gradual reduction of mental workload throughout the acquisition phase and between 5-minute and 48-hour retention tests. Also, there was a clear distinction in mental workload between the three ID conditions. According to the Optimal Challenge Point Framework, task difficulty consists of nominal and functional difficulty (Goudagnoli & Lee, 2004). Nominal difficulty is an absolute term. In a Fitts' Law task, the ID represents the amount of information that the task contains (*e.g.*, an ID of four indicates four bits of information). Thus, a higher ID would take more time to complete than a lower ID (Fitts, 1954; Fitts & Peterson, 1964), regardless of the efficiency of an individual. Thus, ID implies nominal difficulty. In contrast, functional difficulty is a relative difficulty (*i.e.*, an individual may perform better than another individual at the same ID). In the human system, however, assessing functional difficulty is challenging. Fitts and Posner's (1967) learning stage model explains that individuals' cognitive process is slow and conscious in the initial stage and becomes more automatic as they improve the task. Research examining the optimal difficulty has shown that mental workload using NASA-TLX may represent functional difficulty (Akizuki & Ohashi, 2015; Shuggi et al., 2017). Thus, mental workload using NASA-TLX may represent individual differences in the process efficiency. Empirical evidence supported this notion using NASA-TLX that skilled individuals showed lower mental workload scores relative to less skilled individuals (Diekfuss et al., 2017). Further, although this is beyond the scope of the present study, the relationship between performance and NASA-TLX were further supported by neural changes, using electroencephalography (Jaquess et al., 2018). The results of the present study replicated previous findings (Akizuki & Ohashi, 2015; Diekfuss et al., 2017; Jaquess et al., 2018; Shuggi et al., 2017) that the subjective profiles may help explain the mechanism of motor learning regarding the efficiency of processing.

Although the present study replicated previous findings when examining the practice and retention test data, mental workload did not show the difference between ID conditions in the transfer test. That is, when participants performed a dual task, mental workload scores did not represent the differences in task difficulty, while performance data in MT continued to show the differences between the ID conditions. One potential explanation is that the scores of NASA-TLX during the transfer test represented the mental workload of the secondary cognitive task. The support of this is derived from the explicit knowledge questionnaire. As shown in Figure 6.2. the amount of explicit knowledge was higher in the transfer test than other phases. This was because all participants responded, "*I was thinking about animals that start with [C, P, G]*" during the transfer test. Although three participants responded, "*I gave up thinking about animals in the middle of the trial*," the results confirmed that almost all participants were allocating their attention to the secondary task. Additionally, participants practiced the task two days prior to the transfer test. It is assumed from the performance outcome that performance was more automated on Day 3 compared to the beginning of the experiment. As a result, participants were able to allocate their attention to the secondary task regardless of the ID conditions. This may have cancelled out the effect of ID on mental workload. To understand the effect of a secondary task on the primary task in mental workload, future studies should choose a task that naturally forces participants to direct their attention to the primary task. For example, if the environmental variables change (*e.g.*, position, size, or distance of the target) during trial, which forces participants to allocate their attention to both tasks or switch attention between the two tasks, rather than probing their attention only to a secondary task.

The effects of attentional focus

The hypothesis of attentional focus effects on mental workload was not supported. Further, the primary interest of adopting subjective profiles in the present study was whether mental workload provides unique information which may explain the mechanism of performance differences between an EXF and INF. Results from the present study showed that mental workload paralleled the performance results of MT and did not show difference in mental workload between groups. Additionally, although the INF group tended to have a higher number of error taps in the transfer test, there was no trend of difference in mental workload between groups. This result showed that mental workload does not explain performance decrement by an INF. One finding that limited the interpretation of the present study was the lack of group differences. Poolton et al. (2006) proposed that an INF disrupts performance by loading working memory. This loaded working memory should be represented in a higher mental workload score. However, having no difference between groups limited the interpretation of the results only to the differences between ID's and practice effects regardless of the group assignment. Future studies should examine the differences in mental workload in a motor skill that has a distinct performance difference between the EXF and INF groups.

Perceived Competence

Results of the perceived competence were similar to those of mental workload. There was a clear difference between task difficulty conditions, and the perceived competence increased as participants improved the task. However, the results paralleled the performance results, and the data did not show unique information that may explain the attentional focus effects. Recently, the importance of psychological factors in motor skill learning has been suggested (Lewthwaite & Wulf, 2010; Wulf & Lewthwaite, 2016). In the motor behavior domain, various practice variables (*e.g.*, feedback, instruction, practice schedule) have demonstrated to increase competence. For example, providing choices to learners (*i.e.*, autonomy of support) has shown to be effective in motor learning and increase competence (Chiviacowsky, Wulf, & Lewthwaite, 2012; Lewthwaite, Chiviacowsky, Drews, & Wulf, 2015); and providing positive social comparison statements (*i.e.*, enhanced expectancy) has shown the improvements of performance and perception about the personal ability (McKay, Lewthwaite, & Wulf, 2012). Further, perceived competence has been shown to be sensitive to task difficulty (Fox, 1997; Frhika et al., 2019). The rationale of adapting a perceived competence questionnaire was that the EXF benefits relative to an INF may be due to a heightened competence. According to the self-determination theory (Deci & Ryan, 1985, 2008), competence, which is considered as one of the psychological needs with relatedness and autonomy, increases motivation. Thus, this increased competence may, in turn, affect motivation, which may affect the beneficial learning effect of an EXF. Although the interpretation of the present results is challenging due to the lack of performance difference between the EXF and INF groups, attentional focus may not affect perceived competence, considering no difference in competence when performance showed a trending difference between the INF and CON groups in the transfer test. One potential explanation is that EXF and INF cues are movement specific. Although the term 'external' may imply thoughts that are not related to the task or simply outside the body, an EXF is, by definition, attention to the effects of the *movement* on the environment; and the term 'internal' may indicate thoughts or feeling that emerges in the performers' cognition. However, an INF is restricted to attention to the body *movement* (Wulf et al., 1998). Consequently, instructional strategies that stimulate components related to motivation (*e.g.*, autonomy, social comparison, relatedness) may affect competence. More recently, Wulf and Lewthwaite (2016) and Wulf et al. (2017) theorized the OPTIMAL theory, proposing that autonomy of support and enhanced expectancy serve as motivational factors while an EXF functions to increase focus to the task goal, which collectively increases action-goal coupling process and promote optimization of motor learning. Thus, an EXF or INF cue may not affect components that influence motivation. Although mental workload and perceived competence may be important measurement tools to further develop motor learning theories, these parameters may not explain the underlying mechanism specific to the EXF and INF effects.

Explicit Knowledge

The effects of difficulty and learning

The results showed that the amount of explicit knowledge decreased with time (hypothesis regarding the amount was not supported), and the EXF group resulted in a greater amount of explicit knowledge (the hypothesis was not supported). Additionally, we found that a more difficult condition resulted in a greater amount of explicit knowledge (was not hypothesized). For the types of explicit knowledge, the results showed that the EXF group showed a greater proportion of explicit knowledge about techniques and smaller proportion of self-reflection rules relative to the expected values (hypothesis was not supported).

Research examining cognitive tasks (*e.g.*, mathematical calculation, geometric reasoning) has theorized that learning begins with accumulation of declarative knowledge (*i.e.*, explicit knowledge), and the memory structure relies more on procedural knowledge (*i.e.*, implicit knowledge) as individuals improve skills (Anderson, 1982). Although there is no consensus regarding the point of shifts from an accumulation of explicit knowledge to the replacement of explicit knowledge with procedural knowledge, the present study hypothesized that explicit knowledge would increase because the duration of the acquisition phase was limited. Our results showed a *decrease* in explicit knowledge with practice while improving performance. Since implicit knowledge in the present study can be assumed only by performance outcome, this result suggests that a shift from explicit knowledge to implicit knowledge occurred relatively at the early stage of the experiment. One potential explanation, and the limitation of the present study, is participants had already been able to perform the given task at the beginning of the experiment. Using Fitts and Posner's three stage model (1967), participants may have been in the middle (associative) stage at the beginning of the experiment rather than the initial (cognitive) stage. Another explanation is that the nature of the task allowed participants to become relatively automatic at an earlier stage of the experiment. Although the number of trials is important when investigating implicit and explicit knowledge (Maxwell et al., 2001), previous studies examining implicit and explicit learning adopted discrete motor skills (Lam et al., 2009; Koudijker et al., 2007; Masters, 1992; Maxwell et al., 2001; Poolton et al., 2006). The present study was a reciprocal tapping task where participants performed multiple aiming attempts in each trial. As a result, even though participants performed only nine trials for each block with three trials of each ID condition, hundreds of taps were made for each ID by the end of Block 1, especially for the two lower ID conditions.

Regarding task difficulty and explicit knowledge, explicit knowledge was greater in the most difficult condition compared to the easiest condition. In the previous literature, the emphasis of the work was the comparison between an implicit and explicit learning strategy in one motor skill (*e.g.*, Beilock, Carr, MacMahon, & Starkes, 2002; Green & Flowers, 1991; Masters, 1992). The present study revealed that the amount of explicit knowledge is also dependent upon the difficulty of motor skills. This finding was in line with the existing cognitive process and learning theories in that more difficult tasks require greater working memory and conscious processing (Fitts & Posner, 1967; Schneider & Shiffrin, 1977). Therefore, the results indicate that participants in the present study were using more working memory and relying on explicit knowledge when performing the difficult condition due to an increased need for processing information. Although the optimal point of difficulty that facilitates greatest motor learning has been theorized based on the amount of information carried in the task (*i.e.*, information theory) (Goudagnoli & Lee, 2004), the present study showed that explicit knowledge is a useful tool to examine the optimal difficulty. Conscious processing implies a greater use of explicit knowledge in retrieving and integrating information from long-term memory (Anderson, 1982; Maxwell & Masters, 2004), which was reflected on the increase in the subjective mental workload and explicit rules in the present study. This theoretical approach may be more tangible. The load of working memory has been examined by manipulating the external constraints, such as demanding participants to perform a secondary task (*e.g.*, Abertney, 1988; Masters, 1992) or changing task difficulty (Akizuki & Ohashi, 2015). However, this method reflects only nominal difficulty. Since individuals' working memory is also influenced by their own capacity, explicit knowledge may be a testable approach to develop the theories in this area.

The effects of attentional focus

In contrast to the traditional theories of learning, proposing that a skill learning begin with an accumulation of explicit knowledge (Anderson, 1982; Fitts & Posner, 1967), more recent theories have shown that explicit learning may not be necessary or even harmful to implicit learning (Green & Flowers, 1991), especially under pressure (Lam et al., 2009; Masters, 1992; Poolton et al., 2006). Upon these findings, Maxwell and Masters (2002) and Poolton et al. (2006) proposed that the detrimental effect of an INF is due to an increase in explicit knowledge about conscious control of the movements. Empirical evidence shows that the amount of explicit knowledge was either none-differential (Koudijiker et al., 2007) or the INF group resulted in a greater explicit knowledge (Poolton et al., 2006). Accordingly, we hypothesized that the EXF group would have less explicit knowledge. However, the results of the present study showed the amount of explicit knowledge was greater in the EXF group in the most difficult condition relative to the easiest condition during the retention tests, while such difference was not evident for the INF and CON groups. Considering this greater amount of explicit knowledge in the EXF did not negatively affect performance, it is possible to conclude that the amount of explicit knowledge may not be an important factor. However, it is important to note that participants in the present study reported one or two explicit rules, whereas samples from previous studies reported a greater amount of explicit knowledge (Koudjiker et al., 2007; Poolton et al., 2006). Therefore, the amount of explicit knowledge may still play an important role; however, it may only affect performance when participants rely more on explicit knowledge during motor execution.

To thoroughly understand the effect of explicit knowledge on performance, the types of explicit knowledge, in addition to the quantity, was assessed. The results revealed that the EXF group had a higher proportion of explicit rules about techniques and lower proportion of self-reflective/evaluative thoughts compared to the expected values. In contrast, the INF group resulted in a lower proportion of explicit rules about techniques. Perrault and French (2015) found that the INF group had a greater proportion of thoughts about self-conscious/evaluative thoughts relative to the CON group. Although the present study qualitatively replicated this finding by showing a higher percentage of thoughts about self-evaluation in the INF group (14.65%) compared to the EXF group (7.02%), quantitative method using the inferential statistics showed that this higher proportion was not significantly higher than the expected value. This indicates that it may be *the reduction of thoughts* about technique, rather than increased thoughts of self-conscious, that hampers performance.

Our results about the decreased proportion of thoughts about techniques in the INF are congruent with the hypothesis proposed by Zentgraf and Munzert (2009). The hypothesis proposes that the disruption by an INF occurs when the conflict between performing the task-relevant features and complying with INF instructions is large. In that study, novices observed experts' juggling performance and the EXF group received instructions of experts' characteristics about the ball height (*i.e.*, trajectory of the balls) while the INF group received instruction of experts' characteristics about arm movements. The important finding was that both groups of participants implicitly learned a goal behavior from demonstration and explicitly learned the attentional focus instructions. The results showed that the EXF group showed similar ball flight characteristics to the demonstration and the INF group showed similar arm movement characteristics to the demonstration. Since important task-relevant features are implicitly learned by observational learning, the resemblance of the results in the CON group to the EXF group further strengthened this hypothesis. Therefore, the EXF benefits are due to the focus on the task-relevant feature and the INF detrimental effects are due to the neglected attention to the task-relevant features.

If an INF disrupts performance due to addition of loads to working memory proposed by Poolton et al. (2006), the EXF in the present group would have performed worse by having a greater quantity of explicit rules, and the mental workload may have been higher in the EXF group. The OPTIMAL theory (Wulf & Lewthwaite, 2016) proposes that an EXF, autonomy support, and enhanced expectancy collaboratively increases the focus on the task goal while an INF promotes self-focus. Our results partially support the theory in that an EXF may increase attention to the task goal. However, the data did not show an INF increases self-focus. Rather, an INF attenuates attention to the task goal.

The present study showed that explicit knowledge may provide unique information beyond performance outcomes, and therefore, may serve as a mediating factor of the attentional focus effects. However, future studies should be directed to confirm the findings in other motor skills and to identify the methodology to determine the degree to which an INF cue is close to the task-relevant features. Additionally, it is important to note that an INF showed a higher proportion of self-focus, although it was only qualitatively evidential. As mentioned, an INF is specific to movement cues and has no implication of self-evaluation and reflection. However, self-evaluative thoughts were qualitatively higher in the INF relative to the EXF group. Future studies should examine how attention to body parts/movements affect cognition.

Magnitude of Compliance

Traditionally, manipulation checks have been administered simply to confirm instructional strategies are adopted by participation. However, the present study showed that the compliance checks may provide more information. Specifically, our results, in general, showed that the magnitude of compliance to given instructions was lower in the difficult conditions relative to easier conditions. Further, the magnitude of compliance changes throughout the acquisition and testing phases by gradually increasing the magnitude. These results indicate that the interpretation of performance results may need to be adjusted based on the degree to which participants follow an assigned instruction, especially for a learning design study. At the early stage of the acquisition phase, cognitive processes may have been occupied to process information about the task (Fitts & Posner, 1967). Therefore, participants may not be able to follow an assigned instruction until they reach a certain level. This may explain the previous literature showing no difference between an EXF and INF at an early stage of the experiment (McNevin et al., 2003; Wulf et al., 1998 Exp.2; Wulf et al., 1999). The results also provide a strong implication for practitioners that provision of instructions may be adjusted based on the difficulty of the task and the skill level of the performers. Regarding the effects of instructions, the INF showed lower compliance relative to the CON in the lower ID's, but during the high ID condition, both EXF and INF groups showed lower compliance relative to the CON group. While the latter result was not surprising since the instruction to the CON group was to do their best, the former results showed the differential effect of compliance based on the attentional focus cues. The results also partially supported that an INF led to a lower compliance score (Lohse et al., 2014; Raisbeck et al., 2020). A potential explanation may be available from the task-relevance hypothesis by Zentgraf and Munzert (2009). Since an INF cue was a derivative of the task goal, participants may have perceived it as challenging to comply with the INF instruction.

Conclusion

The present study showed that mental workload and perceived competence are sensitive measures to understand the effects of task difficulty and learning effects on perception. Although our results supported that mental workload is a useful tool that may indirectly reflect working memory and information efficiency, both mental workload and perceived competence paralleled performance outcomes, and thus did not mediate the attentional focus effects. Explicit knowledge, on the contrary, may have a strong link to attentional focus. The results showed that the type of explicit knowledge is as important as the quantity of explicit rules, as shown in previous studies. Further, explicit knowledge differed by attentional focus and provided unique information that may develop attentional focus theories.

CHAPTER VII

EXECUTIVE SUMMARY

More than two decades of literature shows a beneficial effect of an EXF over an INF (Wulf, 2013), which has been supported by the CAH (McNevin et al., 2003; Wulf et al., 2001). Upon the findings suggesting the moderation effect by task difficulty (Landers et al., 2005; Wulf et al., 2007) and the inconsistency regarding the bidirectional effects of EXF and INF by the CAH standpoint, understanding the complex human behavior and cognition from a single theoretical framework may provide limited insights. To this end, the present study examined the effects of attentional focus with a multi-theoretical approach. In Chapter IV, performance data were investigated from theories based on the information theory (Fitts & Posner, 1967; Schneider & Shiffrin, 1977), hypothesizing that the EXF group would perform better at the medium difficulty condition when participants require a controlled process but not too overwhelming, while the CON group would perform better at the easy condition when the cognitive process is theoretically automatic. In Chapter V, variability of the joint angular velocity was examined from the theories of variability. Increasing movement or time series variability may indicate more adaptable and flexible movement coordination, which may decrease performance variability (Bernstein, 1967; Newell, 1986; Stergiou & Decker, 2010). It was hypothesized that the EXF group would have a higher movement and times series variability than the INF group. Lastly, in Chapter VI, attentional focus was viewed from the cognitive perspective by examining subjective profiles of participants. It was hypothesized that the EXF group would have a lower mental workload and higher perceived competence, which may mediate the attentional focus effects on enhanced performance. Further, Poolton et al. (2006) suggested that the attentional focus effects specific to the EXF/INF paradigm is rather the disruption of working memory by an INF due to an increase in explicit knowledge, while Perreault and French (2015) proposed that an INF induces self-conscious, evaluative thoughts which causes micro-choking. Thus, it was hypothesized that the INF group would have a higher amount of explicit knowledge and greater proportion of explicit knowledge about self-evaluating thoughts.

Overall discussion here emphasizes on integrating the results from different theoretical frameworks specific to the effect of attentional focus. The interpretation regarding task difficulty and learning effects are discussed in detail in each chapter. For performance results:

A) Both MT and error taps improved in all difficulty and all attentional focus groups, with more errors and slower MT for more difficult conditions.

B) there was no group difference during practice and retention tests.

C) there was no interaction of task difficulty by attentional focus.

D) In the transfer test when working memory was loaded by a secondary task, the number of error taps showed a marginal effect, suggesting that the INF group resulted in a greater number of errors compared to the CON group. The measurement of the precise accuracy confirmed that the variability of performance was significantly larger in the INF relative to the CON group.

For variability of joint angular velocity, the results showed:

E) SD of the joint angular velocity increased with practice while CV and SampEn decreased, and all variability metrics showed a greater variability for more difficult tasks.

F) No group difference was found regarding the learning effects. However, CV, not SD nor SampEn, showed a marginal effect, suggesting that the INF group resulted in a *lower* variability relative to the CON group.

Lastly, the results of subjective profiles showed:

G) Mental workload decreased, and perceived competence increased with performance improvements; more difficult tasks showed a higher mental workload score and lower competence score.

H) No difference between groups was found in mental workload and perceived competence.

I) The amount of explicit knowledge reduced as participants improved with the task; a greater amount of explicit knowledge was evident for more difficult conditions; and the EXF group was higher in the number of explicit rules during the retention tests (at the most difficult condition).

J) The type of explicit knowledge showed that the INF group resulted in a lower proportion of explicit knowledge about techniques, while the EXF group showed a higher proportion of techniques and lower proportion of self-evaluative thoughts.

From these results, one of the main questions was the hypothesis of the interaction effect by task difficulty. The present study adopted Fitts' law (ID) to measure task difficulty. Fitts' law task is designed to test the information capacity. A greater ID represents greater information to be carried out. Results of the improved MT indicates that the capacity of information process became more efficient. This assumption was indirectly supported from G) and I). That is, a reduction of mental workload may indicate a reduced working memory and the reduction of explicit knowledge indicates that the motor execution relies more on the procedural memory system, which consumes less attentional resources. Although the degree of automaticity is unclear, these results with performance data showed that participants became more automatic with practice. In the same rationale, a higher mental workload and greater explicit knowledge during a difficult task condition indicates that a cognitive process during the high difficult condition was a controlled process. Despite these results, there was no group difference. Thus, our data suggest that the attentional focus was not affected by cognitive process. However, it is important to note that the results were still equivocal because task difficulty is not a single dimensional concept. At the same ID, some participants performed better than the others (the functional difficulty). Consequently, this individual difference made the distinction between task difficulty conditions unclear. Therefore, more investigation is warranted to confirm the effect of task difficulty and attentional focus.

Two more primary questions of the present dissertation were a bidirectional proposition (*i.e.*, an EXF superiority and INF inferiority) of the CAH and the mechanism of attentional focus. Regarding the bidirectional effect, for attentional focus to be bidirectional, an EXF requires to be superior to and an INF requires to be inferior to a non-attentional focus strategy (*i.e.*, CON, or 'do your best' group). The present study did not show evidence to support the EXF benefits, while an INF was inferior to the non-attentional focus strategy. Poolton et al. (2005) proposed that the attentional focus effects specific to EXF/INF occur due to an INF detrimental effect by disrupting working memory. Our results partially supported this proposition in that there was a unidirectional, but not bidirectional effect (the discussion about working memory is described later). However, this effect was not evident during practice or retention tests. We believe the absence of the effect during these phases is related to the skill level of the participants. Although the task was novel to participants, they have performed a variety of reaching, transferring, and aiming tasks prior to participating in this study. As a result, even if there were a disruptive effect of an INF, participants may have had room in the attentional resources to compensate for the INF effect. Therefore, the INF effect surfaced only when working memory was loaded by a secondary task.

The aim of the present study was to determine a potential mechanism of the attentional focus effects by investigating the attentional focus effects from multiple theoretical perspectives. In the present study, two main variables showed effects related to attentional focus when the INF group performed more poorly than the CON group in the transfer test: The type of explicit knowledge and CV of the joint angular velocity. Poolton et al. (2005) found that an INF led to a greater quantity of explicit knowledge and more explicit knowledge about movement execution. Greater thoughts about motor execution during trial indicates that performers were more consciously monitoring their performance, and thus consuming working memory. Therefore, it was proposed that an INF has a detrimental effect because of the added working memory consumption due to increased explicit knowledge, especially when working memory is loaded (Masters & Maxwell, 2002; Poolton et al., 2006). However, the examination of explicit knowledge showed that the quantity was greater in the EXF group with no detrimental effect on performance. While the present study further supported that explicit knowledge is a useful tool to understand motor learning, our results did not support the working memory disruption.

Another candidate of the attentional focus mechanism is evidenced by the OPTIMAL theory (Wulf & Lewthwaite, 2015). The theory suggests that an INF evokes self-conscious processing (Perrault & French, 2015), and this self-conscious or self-evaluative thoughts causes micro-choking, which affects performance. Qualitatively, the present study replicated the findings by Perrault and French (2015) in that the proportion of self-evaluative thoughts of the INF group was higher than the proportion of self-evaluative thoughts in the EXF group. However, the categories of explicit knowledge by a quantitative analysis showed the proportion of self-evaluative thoughts was not higher than the expected value in the INF group. Rather, the INF group showed a significantly lower proportion of thoughts about techniques while the EXF resulted in a higher proportion of techniques and lower proportion of self-evaluative thoughts. This result suggests that an INF detracted participants' attention away from the thoughts that were relevant to the task goal features, while an EXF increased attention toward the task goal.

Accordingly, the present results did not agree with a hypothesis about increased self-evaluative thoughts by an INF.

The present data supports the hypothesis that was proposed by Zentgraf and Munzert (2009) (we name it here as the task-goal feature hypothesis). This hypothesis proposes that the attentional focus effects depend on the extent to which an attentional focus cue is closer to the task-goal features. In that study, participants practiced a juggling task while observing an expert model. For the EXF group, attention was directed toward the trajectory of the ball, which is the key task-goal feature of the juggling task, and attention was directed towards the elbow movements for the INF group, which is a derivative of the task goal feature. Compared with experts, the ball trajectory was similar in the EXF than the INF groups, whereas the elbow movements were similar to experts in the INF group relative to the EXF group. The key finding of the study was that the CON group showed the similar ball trajectory to the EXF group. Since all groups observed the same expert model, the relevant and salient features (*i.e.*, ball trajectory) should have been picked up through observation. Thus, the similar behavior between the CON and EXF was expected. However, when attention was detracted from this feature (*i.e.*, INF), behavior differed. From these results, Zentgraf and Munzert implied that if an INF cue is closer to the task goal feature, motor behavior would be similar to an CON or EXF, whereas an INF cue that is far from the task goal feature would result in a differential behavior between performance with an EXF.

Although Zentgraf and Munzert (2009) proposed an intriguing hypothesis, they did not provide a potential mechanism or how attentional focus affects movements. The data from the present study may strengthen this hypothesis. In the present study, it was shown from the results of J (explicit knowledge) that directing individuals' attention to body movements drove participants' attention away from the task goal features. This may have affected the reduction of the joint angular velocity variability (presented in F), which, in turn, increased performance variability (presented in D). Therefore, the task goal feature hypothesis agrees with the present data that were tested from different theoretical frameworks.

An advantage of this hypothesis is that it is more comparable with different motor control/learning theories. Although there are fundamental differences, a similar concept between theories from cognitive/experimental psychology (*e.g.*, attentional focus theories, explicit/implicit learning theories, and information theory) and motor control theories (*e.g.*, dynamical systems theory) is that the key to the formation of a motor output/command is a task goal. The theories related to the dynamical systems theory proposes that behavior is self-organized by constraints, which indicates that a behavior is shaped by a task goal. Theories in psychology or attentional focus (*e.g.*, the CAH, the OPTIMAL theory) generally agree with the concept that the selection of a motor output (*i.e.*, action-perception coupling) is best planned by its intended effect (the action effect hypothesis by Prinz, 1997) or that the action-perception is coupled by making an association (sharing the common codes) between the action and the expected consequences of perception by its action (the ideomotor theory by Elsner & Hommel, 2001; Hommel, 2001). Task goal features are selected explicitly (*e.g.*, attentional focus) or implicitly (*e.g.*, observation, experience) from the environment and/or internal representations. Then, attentional focus may play a critical role in channeling certain stimuli to be processed, and the information received and processed at this stage would determine the motor output configuration. Attention to the task goal features would produce a motor output that is optimal with given constraints. However, directing attention away from the task goal features would lead to a production of a motor output configuration that is less than optimal. This undesired motor output configuration may be represented in an increase or decrease in variability depending on the attractor state of the task. Therefore, although theories based on the information theory and dynamical systems theories are fundamentally different, integrating different theories may provide a testable and comparable theory that develop the understanding of motor skill acquisition and attentional focus.

In the present study, the EXF/INF phenomenon was examined from multiple theoretical frameworks. One would wonder if one theory should be denied over another. However, one theoretical structure relies on specific experimental paradigms, tasks, measurement tools, and premise that are unique to the theory. Thus, it would be more beneficial to extract the advantages of different frameworks and compare the findings that agree and disagree to develop the mechanism of motor behavior. From the present study, it is evident that theories of variability provided more information regarding the mechanism of motor control (*i.e.*, differences and changes between joint variability by attentional focus, task difficult manipulation, and practice). However, variability alone may not be sufficient to explain an underlying mechanism of attentional focus, cognitive process, and action-perception coupling. Therefore, motor behavior may be explained better by integrating theories from multiple disciplines

Limitations

Although the present study provided unique information that may develop the attentional focus mechanism, various limitations were identified. Regarding the study design, participants performed one trial for each ID during the testing phase, while they practiced three consecutive trials per ID in each block. This limited a direct comparison between the practice and testing phase due to potential fatigue effects. Future study may provide the equal number of trials (*e.g.*, three trials for each ID during the testing phase). Another limitation was that participants practiced three different difficulties, which may have affected the results. To examine the effect of task difficulty, the task difficulty factor may be treated as a between-subject design. Related to this concern, task difficulty is affected not only by ID (nominal difficulty) but also by functional difficulty. Assigning participants into conditions based on the baseline performance would eliminate individual differences. Regarding the analysis of variability, the present study examined a temporal structure of variability in the joint motion where time series variability is generally measured in the trial-to-trial fluctuation of performance variability. As indicated in the discussion in Chapter V, the optimal metrics to measure (*e.g.*, Recurrence Quantification Analysis) and parameters (*e.g.*, r and m for SampEn) are still unclear since this method was exploratory. Future studies should be directed to develop and confirm if the time series variability of the joint kinematics would provide meaningful information. Further, the angular velocity variability represents coordination between two body segments.

However, whether similar interpretation is available if the inter-segment variability (relationship between the variability of shoulder and elbow) is measured. Lastly, for explicit knowledge, the present study showed a distinctive difference from previous studies (*e.g.*, Poolton et al., 2005; Masters & Maxwell, 2002). However, the number of responses was different since the task may have been simpler relative to the skills used by Poolton et al. and Masters and Maxwell. Future studies should be directed to consider the complexity of motor skills when examining the amount of explicit knowledge.

REFERENCES

Abdollahipour, R., Palomo Nieto, M., Psotta, R., & Wulf, G. (2017). External focus of attention and autonomy support have additive benefits for motor performance in children. *Psychology of Sport and Exercise, 32*, 17-24.

Abdollahipour, R., Wulf, G., Psotta, R., & Nieto, M. P. (2015). Performance of gymnastics skill benefits from an external focus of attention. *Journal of Sports Science, 33*(17), 1807-1813.

Adams, J.A. (1987). Historical review and appraisal of research on the learning, retention, and transfer of human motor skills. *Psychological Bulletin, 101*(1), 41–74.

Adams, J. A. (1971). A Closed-loop theory of motor learning. *Journal of Motor Behavior, 3*(2), 111–50.

Adams, J. A., & Dijkstra, S. (1966). Short-term memory for motor responses. *Journal of Experimental Psychology, 71,* 314-318.

Akizuki, K., & Ohashi, Y. (2015). Measurement of functional task difficulty during motor learning: What level of difficulty corresponds to the optimal challenge point? *Human Movement Science, 43,* 107-117.

Alorani, S. M., Glazebrook, C. M., Sibly, K. M., Singer, J., & Steven, P. (2019). Anticipatory postural adjustments during a Fitts' task: Comparing young and older adults and the effects of different foci of attention. *Human Movement Science, 64*, 366-377. Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychological Review, 89*, 369-406.

Asadi, A., Farsi, A., Abdoli, B., Saemi, E., & Porter, J. M. (2019). Directing attention externally and self-controlled practice have similar effects on motor skill performance. *Journal of Motor Learning and Development, 7,* 141-151.

Attneave, F. (1959). Applications of information theory to psychology: *A summary of basic concepts, methods, and results.* New York: Holt, Rinehart & Winston.

Bahmani, M., Diekfuss, J. A., & Kharestani, M. (2018). Does motor imagery modality-dominance influence the effectiveness of attentional focus instructions. *International Journal of Psychology, 49,* 1-19.

Becker, K. A., Fairbrother, J. T., & Couvillion, K. F. (2018). The effects of attentional focus in the preparation and execution of a standing long jump. *Psychological Research, 84*(2), 285-292.

Becker, K.A., & Smith, P.J.K. (2015). Attentional focus effects in standing long jump performance: Influence of broad and narrow internal focus. *Journal of Strength and Conditioning Research, 29*(7), 1780-178.

Beggs, W. D. A., & Howarth, C. I. (1972). The accuracy of aiming at a target: Some further evidence for a theory of intermittent control. *Acta Psychologica, 36,* 171-177.

Beilock, S. L., Bertenthal, B. I., McCoy, A. M., & Carr, T. H. (2004). Haste does not always make waste: Expertise, direction of attention, and speed versus accuracy in performing sensorimotor skills. *Psychonomic Bulletin & Review, 11*(2), 373-379.

Beilock, S. L., & Carr, T. H. (2001). On the fragility of skilled performance: What governs choking under pressure? *Journal of Experimental Psychology. General, 130,* 4, 701-25.

Beilock, S. L., Carr, T. H., MacMahon, C., & Starkes, J. L. (2002). When paying attention becomes counterproductive: Impact of divided versus skill-focused attention on novice and experienced performance of sensorimotor skills. *Journal of Experimental Psychology: Applied, 8*(1), 6-16.

Beilock, S. L., & Gray, R. (2007). 'Why do athletes choke under pressure?', in Tenenbaum, G. & Eklund, R. C. (Eds.). The handbook of sport psychology (3rd ed.). Hoboken, NJ: John Wiley & Sons Inc., pp. 425-444.

Beilock, S. L., & Gray, R. (2012). From attentional control to attentional spillover: A skill-level investigation of attention, movement, and performance outcomes. *Human Movement Science, 31*, 1473-1499.

Beilock, S. L., Wierenga, S. A., & Carr, T. H. (2002). Expertise, attention, and memory in sensorimotor skill execution: Impact of novel task constraints on dual-task performance and episodic memory. *The Quarterly Journal of Experimental Psychology Section A*, *55*(4), 1211–1240.

Bell, J. J., & Hardy, J. (2009). Effects of attentional focus on skilled performance in golf. *Journal of Applied Sport Psychology, 21*, 163-177.

Bernier, M., Codron, R., Thienot, E., & Fournier, J.F. (2011). The attentional focus of expert golfers in training and competition: a naturalistic investigation. *Journal of Applied Sport Psychology, 23*(3), 326–341.

Bernier, M., Trottier, C., Thienot, E., & Fournier, J. (2016). An investigation of attentional foci and their temporal patterns: A naturalistic study in expert figure skaters. *The Sport Psychologist, 30*(3), 256–266.

Bernstein, N. A. (1967). *The coordination and regulation of movements*. London: Pergamon Press.

Berry, D. C. & Broadbent, D. E. (1987). The combination of explicit and implicit learning processes in task control. *Psychological Research, 49,* 7-15.

Berry, D. C., & Broadbent, D. E. (1988). Interactive tasks and the implicit-explicit distinction. *British Journal of Psychology, 79*, 273-285.

Brach, J.S., Berlin, J.E., VanSwearingen, J.M., Newman, A.B., & Studenski, S.A. (2005). Too much or too little step width variability is associated with a fall history I, older persons who walk at or near normal gait speed. *Journal of NeuroEngineering Rehabilitation, 2*(21).

Broadbent, D. (1958). *Perception and Communication.* London: Pergamon Press.

Broderick, M. P., & Newell, K. M. (1999). Coordination patterns in ball bouncing as a function of skill. *Journal of Motor Behavior, 31*(2), 165-188.

Cherry, C. E. (1953). Some experiments on the recognition of speech, with one and with two ears. *The Journal of the Acoustical Society of America, 25*(5), 975-979.

Chiu, S-L., Chou, L-S. (2013). Variability in inter-joint coordination during walking of elderly adults and its association with clinical balance measures. *Clinical Biomechanics, 28*(4), 454–458.

Chiviacowsky, S., Wulf, G., & Wally, R. (2010). An external focus of attention enhances balance learning in older adults. *Gait and Posture, 32,* 572-575.

Christina, R.W. (1973). Influence of enforced motor and sensory sets on reaction latency and movement speed. *Rese Quarterly. American Association for Health, Physical Education, and Recreation, 44*(4), 483–7.

Christina, B. & Alpenfels, E. (2014). Influence of attentional focus on learning a swing path change. *International Journal of Golf Science, 3,* 35-49.

Chua, L.-K., Wulf, G., & Chiviacowsky, S. (2018). Onward and upward: Optimizing motor performance. *Human Movement Science, 60*, 275-284.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences.* New York, NY: Routledge Academic.

Cole, G., Gellatly, A., & Blurton, A. (2001). Effect of object onset on the distribution of visual attention. *Journal of Experimental Psychology: Human Perception and Performance,27*(6), 1356-1368.

Conroy, D. E., Coatsworth, J. D., & Fifer, A. M. (2005). Testing dynamic relation between perceived competence and fear of failure in young athletes. *Revue Europe´enne de Psychologie Applique´e, 55*, 99–110.

Conway, A. R. A., Cowan, N., & Bunting, M. F. (2001). The cocktail party phenomenon revisited: The importance of working memory capacity. *Psychonomic Bulletin & Review, 8*(2), 331-335.

Côté, J.N., Raymond, D., Mathieu, P.A., Feldman, A.G., & Levin, M.F. (2005). Differences in multi-joint kinematic patterns of repetitive hammering in healthy, fatigued and shoulder-injured individuals. *Clinical Biomechanics, 20*(6), 581–590.

Crossman E. R. F. W. (1959). A theory of the acquisition of speed skill. *Ergonomics, 2*(2), 153–66.

Davids, K., Glazier, P., Arajo, D., & Bartlett, R. (2003). Movement systems as dynamical systems: The functional role of variability and its implications for sports medicine. *Sports Medicine, 33*(4), 245–60.

De Bruin, E. D., Swanenburg, J., Betschon, E., & Murer K. (2009). A randomized controlled trial investigating motor skill training as a function of attentional focus in old age. *BioMed Central: Geriatrics, 9*(15), 1-10.

Deci, E. L., & Ryan, R. M. (1985). *Intrinsic motivation and self-determination in human behavior.* New York: Plenum.

Deci, E. L., & Ryan, R. M. (2008). Self-Determination Theory: A macrotheory of human motivation, development, and health. *Canadian Psychology, 49*, 182–185.

De Melker Worms, J. L. A., Stins, J. F., van Wegen, E. E. H., . . ., & Loram, I. D. (2017a). Effects of attentional focus on walking stability in elderly. *Gait & Posture, 55*, 94-99.

De Melker Worms, J. L. A., Stins, J. F., van Wegen, E. E. H., De Loram, I. D., & Beek, P. (2017b). Influence of focus of attention, reinvestment and fall history on elderly gait stability. Physiological Reports, 5(1), doi: 10.14814/phy2.13061

Diekfuss, J. A., Rhea, C. K., Schmitz, R. J., . . ., & Raisbeck, D. L. (2018). The influence of attentional focus on balance control over seven days of training. *Journal of Motor Behavior, 51*(3), 281-292.

Diekfuss, J. A., & Raisbeck, L. D. (2017). Attentional focus in NCAA Division 1 golfers. *Journal of Motor Learning and Development, 5*, 240-251.

Diekfuss, J. A., & Raisbeck, L. D. (2016). Focus of attention and instructional feedback from NCAA Division 1 collegiate athletes. *Journal of Motor Learning and Development*, *4*, 262-273.

Diekfuss, J. A., Ward, P., & Raisbeck, L. D. (2017). Attention, workload, and performance: A dual-task simulated shooting study. *International Journal of Sport & Exercise Psychology, 15*(4), 423-237.

Dinz, A., Wijnants, M. L., Torre, K., . . ., & Delignieres, D. (2011). Contemporary theory of 1/f noise in motor control. *Human Movement Science, 30*, 889-905.

Ducharme, S. W., Wu, W. F. W., Lim, K., Porter, J. M., & Geraldo, F. (2015). Standing long jump performance with an external focus of attention is improved as a result of a more effective projection angle. *Journal of Strength and Conditioning Research, 30*(1), 276-281.

Duke, R. A., Cash, C. D., & Allen, S. E. (2011). Focus of attention affects performance of motor skills in music. *Journal of Research in Music Education, 59*(1), 44-55.

Elliott, D., Hansen, S., Mendoza, J., & Tremblay, L. (2004). Learning to optimize speed, accuracy, and energy expenditure: A framework for understanding speed-accuracy relations in goal-directed aiming. *Journal of Motor Behavior, 36*(3), 339-351.

Elliott, D., Helsen, W. F., & Chua, R. (2001). A century later: Woodworth's (1899) Two-Component Model of goal-directed aiming. *Psychological Bulletin, 127*(3), 342-357.

Elliott, D., & Khan, M. (2010). *Vision and goal-directed movement: Neurobehavioral perspectives.* Human Kinetics: Champaign, IL.

Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 229-240.

Fairbrother, J. T., Post, P. G., Whalen, S. J. (2016). Self-reported responses to player profile questions show consistency with the use of complex attentional strategies by expert Horseshoe pitchers. *Frontiers in Psychology, 7,* 1- 8.

Fietzer, A. L., Winstein, C. J., & Kulig, K. (2018). Changing one's focus of attention alters the structure of movement variability. *Human Movement Science, 62*, 14-24.

Fitts, P.M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47*(6), 1-11.

Fitts, P. M., & Deininger, R. L. (1954). S-R compatibility: Correspondence among paired elements within stimulus and response codes. *Journal of Experimental Psychology, 48*(6), 483-492.

Fitts, P. M., & Peterson, J. R. (1964). Information capacity of discrete motor responses. *Journal of Experimental Psychology, 67*(2), 103-112.

Fitts, P. M., & Posner, M. I. (1967). *Human Performance.* Belmont, CA: Brooks/Coke.

Fitts, P. M., & Seeger, C. M. (1953). SR compatibility: Spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology, 46,* 199-210.

Flach, J. M., Guisinger, M. A., & Robinson, A. B. (1996). Fitts' Law: Nonlinear dynamics and positive entropy. *Ecological Psychology, 8*(4), 281-325.

Fredenburg, K. B., Lee, A. M., & Solmon, M. (2001). The effects of augmented feedback on students' perceptions and performance. *Research Quarterly of Exercise and Sport, 72*, 232–242.

Fredricks, J. A., & Eccles, J. S. (2002). Children's competence and value beliefs from childhood through adolescence: Growth trajectories in two male sex-typed domains. *Developmental Psychology, 38*(4), 519–533.

Frikha, M., Chaari, N., Elghoul, Y., Mohamed-Ali, H. H., & Zincovsky, A. V. (2019). Effects of combined versus singular verbal or haptic feedback on acquisition, retention, difficulty, and competence perceptions in motor learning. *Perceptual and Motor Skills*, doi: 10.1177/0031512519842759.

Goldberger, A. L. (1996). Non-linear dynamics for clinicians: Chaos theory, fractals, and complexity at the beside. *The Lancet, 347,* 1312-1314.

Goldberger, A.L., Peng, C-K., & Lipsitz, L.A. (2002). What is physiologic complexity and how does it change with aging and disease? *Neurobiology & Aging, 23*(1),23–26.

Grabiner, P. C., Biswas, S.T., & Grabiner, M. D. (2001). Age-related changes in spatial and temporal gait variables. *Archives of Physical Medicine & Rehabilitation, 82*(1), 31-35.

Green, T. D., & Flowers, J. H. (1991). Implicit versus explicit learning processes in a probabilistic, continuous fine-motor catching task. *Journal of Motor Behavior*, *23*(4), 293–300. https://doi.org/10.1080/00222895.1991.9942040

Greig, M., & Marchant, D. (2014). Speed dependent influence of attentional focusing instructions on force production and muscular activity during isokinetic elbow flexions. *Human Movement Science, 32*,135-148.

Guiard, Y. (1993). On Fitts' and Hooke's laws: Simple harmonic movement in upper-limb cyclical movement. *Acta Psychologica, 82*, 139-159.

Halperin, I., Chapman, D. W., Martin, D. T., & Abbiss, C. (2017). The effects of attentional focus instructions on punching velocity and impact forces among trained combat athletes. *Journal of Sports Sciences*, 1-8 DOI: 10.1080/02640414.2016.1175651

Halperin, I., Williams, K. J., Martin, D. T., Chapman, D. W. (2015). The effects of attentional focusing instructions on force production during the isometric midthigh pull. *Journal of Strength and Conditioning Research,30*(4), 919-923.

Haken, H., Kelso, J. A. S., & Bunz, J. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics*, *51*, 347-356.

Hancock, G. R., Butler, M. S., & Fischman, M. G. (1995). On the problem of two-dimensional error scores: Measures and analysis of accuracy, bias, and consistency. *Journal of Motor Behavior, 27*(3), 241-250.

Hart, S.G. (2006). Nasa-Task Load Index (NASA-TLX); 20 years later. *Proceedings of Human Factors and Ergonomics Society Annual Meeting, 50*(9),904-908.

Hart, S. G. & Staveland, L. E. (1988) *Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research.* In P. A. Hancock and N. Meshkati (Eds.). Human Mental Workload. Amsterdam: North Holland Press.

Hausdorff, J. M., Rios, D. A., & Edelberg, H. K. (2001). Gait variability and fall risk in community-living older adults: A 1-year prospective study. Archives of Physical Medicine and Rehabilitation, 82(8), 1050-1056.

Henry, F. M. (1953). Dynamic Kinesthetic Perception and Adjustment. *Research Quarterly. American Association for Health, Physical Education and Recreation, 24*(2), 176-187.

Henry, F. M., & Harrison, J. S. (1961). Refractoriness of a fast movement. *Perceptual and Motor Skills, 13*, 351-354.

Henry, F.M. (1960). Influence of motor and sensory sets on reaction latency and speed of discrete movements. *Research Quarterly. American Association for Health, Physical Education, and Recreation, 31*(3), 459–68.

Henry, F. M., & Rogers, D. E. (1960). Increased response latency for complicated movements and a “memory drum” theory of neuromotor reaction. *Research Quarterly, 31*,448-458.

Hitchcock, D. R., & Sherwood, D. E. (2018). Effects of changing the focus of attention on accuracy, acceleration, and electromyography in dart throwing. *International Journal of Exercise Science, 11*(1), 1120-1135.

Hodges, N. J., & Ford, P. (2007). Skillful, attending, looking and thinking. *E-Journal Bewegung und Training, 1*, 23-24.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*, *24*, 849–937.

Huys, R., Fernandez, L., Bootsma, R. J., & Jirsa, V. K. (2010). Fitts' law is not continuous in reciprocal aiming. *Proceedings of Royal Society B, 277*, 1179-1184.

Ille, A., Selin, I., Do, M-C, & Thon, B. (2013). Attentional focus effects on sprint start performance as a function of skill level. *Journal of Sports Science, 31(*15), 1705-1712.

Jaquess, K. J., Lo, L-C., Oh, H., . . . & Gentili R. J. (2018). Changes in mental workload and motor performance throughout multiple practice sessions under various levels of task difficulty. *Neuroscience, 393*, 305-318.

James, W. (1890). *The principles of psychology* (Vol.1). New York: Holt.

Joseph, M.E., King, A. C. & Newll, K. M. (2013). Task difficulty and time scales of warm-up and motor learning. *Journal of Motor Behavior, 45*(3), 231-238.

Kal, E. C., van der Kamp, J., & Houdijk, H. (2013). External attentional focus enhances movement automatization: A comprehensive test of the constrained action hypothesis. *Human Movement Science*, *32*, 527-539.

Kal, E. C., van der Kamp, J., Houdjik, H., . . ., & Scherder, E. J. A. (2015). Stay focused! The effects of internal and external focus of attention on movement automaticity in patient with stroke. *Plos ONE, 10*(8), e0136917.

Kearney, P. E. (2015). A distal focus of attention leads to superior performance on a golf putting task. *International Journal of Sport and Exercise Psychology,13*(4), 371-381.

Keele, S. W. (1968). Movement control in skilled motor performance. *Psychological Bulletin*, *70*(6), 387-403.

Keele, S. W., & Posner, M. I. (1968). Processing of visual feedback in rapid movements. *Journal of Experimental Psychology*, *77*(1), 155-158.

Keller, M., Lauber, B., Gottschalk, M., & Taube, W. (2014). Enhanced jump performance when providing augmented feedback compared to an external or internal focus of attention. *Journal of Sport Sciences*, 1-9.

Kelso, J. A. S. (1995). Dynamic patterns: The self-organization of brain and behavior. Cambridge, MA: MIT Press.

Kelso, J.A., & Holt, K.G. (1980). Exploring a vibratory systems analysis of human movement production. *Journal of Neurophysiology*, *43*(5),1183–1196.

Kelso, J.A. (1984). Phase transitions and critical behavior in human bimanual coordination. *American Journal of Physiology-Regulatory, Integrative, and Comparative Physiology*, *246*(6), R1000–1004.

Khan, D. (1973). *Attention and Effort.* Prentice-Hall Inc.: Englewood Cliffs, NJ.

Kim, T., Jimenez-Diaz, J., & Chen, J. (2017). The effect of attentional focus in balancing tasks: A systematic review with meta-analysis. *Journal of Human Sport and Exercise, 12*(2), 463-579.

Knaepen, K., Marusic, U., Crea, S., . . . & Meeusen, R. (2015). Psychophysiological response to cognitive workload during symmetrical, asymmetrical and dual-task walking. *Human Movement Science, 40*, 248-263.

Ko, Y. G., Challis, J. H., & Newell, K. M. (2003). Learning to coordinate redundant degrees of freedom in a dynamic balance task. *Human Movement Science, 22*, 47-66.

Koch, I., Keller, P., & Prinz, W. (2004). The ideomotor approach to action control: Implications for skilled performance. *International Journal of Sport and Exercise Psychology, 2*, 362-375.

Koedijker, J. M., Oudejans, R. R. D., & Beek, P. J. (2007). Explicit rules and direction of attention in learning and performing the table tennis forehand. *International Journal of Sport Psychology, 38*, 227-244.

Lake, D. E., Richman, J. S., Griffin, M. P., Moorman, J. R. (2002). Sample entropy analysis of neonatal heart rate variability. *American Journal of Physiology—Regulatory, Integrative, and Comparative Physiology, 283*, R789-R797.

Lam, W. K., Maxwell, J. P, & Masters, R. (2009). Analogy learning and the performance of motor skills under pressure. *Journal of Sport and Exercise Psychology, 31*, 337-357.

Landers, M., Wulf, G., Wallmann, H., & Gaudagnoli, M. (2005). An external focus of attention attenuates balance impairment in patients with Parkinson's disease who have a fall history. *Physiotherapy, 91,* 152 -158.

Langolf, G. D., Chaffin, D. B., & Foulke, J. A. (1976). An investigation of Fitts' Law using a wide range of movement amplitude. *Journal of Motor Behavior, 8*(2), 113-128.

Lashley, K. S. (1917). The accuracy of movement in the absence of excitation from the moving organ. *American Journal of Physiology, 43*, 169-194.

Lavie, N., Hirst, A., de Fockert, J. W., & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General, 133*(3), 339-354.

Lawrence, G. P., Gottwald, V. M., Hardy, J., & Khan, M. A. (2011). Internal and external focus of attention in a novice form sport. *Research Quarterly for Exercise and Sport, 82*(3), 431-441.

Lewis, B. P., & Linder, D. E. (1997). Thinking about choking? Attentional processes and paradoxical performance. *Personality and Social Psychology Bulletin, 23*, 937-944.

Lewthwaite, R., Chiviacowsky, S., Drews, K., & Wulf, G. (2015). Choose to move: The motivational impact of autonomy support on motor learning. *Psychological Bulletin Review, 22*, 1383-1388.

Lewthwaite, R. & Wulf, G. (2010). Grand challenge for movement science and sport psychology: embracing the social-cognitive-affective-motor nature of motor behavior. *Frontier in Psychology, 23*. doi: 10.3389/fpsyg.2010.00042.

Lipsitz, L. A. (2002). Dynamics of stability: The physiologic basis of functional health and frailty. *Journal of Gerontology: Biological Sciences, 57A*(3), B115-B125.

Lipsitz, L.A., & Goldberger, L. (1992). Loss of “complexity” and aging. Potential applications fractals and chaos theory to senescence. *Journal of American Medical Association, 267*(13), 1806-1809.

Lohse, K. R., Jones, M., Healy, A. F., & Sherwood, D. E. (2014). The role of attention in motor learning. *Journal of Experimental Psychology: General, 143*(2), 930-948.

Lohse, K. R., & Sherwood, D. E. (2012). Thinking about muscles: The neuromuscular effects of attentional focus on accuracy and fatigue. *Acta Psychologica, 140*, 236-245.

Lohse, K. R., Sherwood, D. E., & Healy, A. F. (2011). Neuromuscular effects of shifting focus of attention in a simple force production task. *Journal of Motor Behavior, 43*(2), 173- 184.

Lohse, K. R., Sherwood, D. E., & Healy, A. F. (2010). How changing the focus of attention affects performance, kinematics, and electromyography in dart throwing. *Human Movement Sciences, 29*, 542-555.

Lohse, K. R., Sherwood, D. E., & Healy, A. F. (2014). On the advantage of an external focus of attention: A benefit to learning or performance? *Human Movement Science, 33*, 120-134.

Logan, G. D. (1985). Skill and automaticity: Relations, implications, and future directions. *Canadian Journal of Psychology/Revue Canadienne de Psychologie, 39*(2), 367–386. https://doi.org/10.1037/h0080066

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review*, *95*(4), 492–527.

Magill, R.A. (2007). *Motor Learning and Control: Concepts and applications.* (8th ed.). New York, NY: McGraw-Hill Companies, Inc.

Makaruk, H., Porter, J. M., & Makaruk, B. (2013). Acute effects of attentional focus on shot put performance in elite athletes. *Kinesiology*, *45,* 55-62

Makaruk, H, Porter, J. M., Czaplicki, A., Sadowski, J., & Sacewicz, T. (2012). The role of attentional focus in plyometric training. *Journal of Sports Medicine and Physical Fitness, 52,* 319-327.

Maltin, M. W. (2009). *Cognition* (7th Ed.). New York, NY: John Wiley & Sons, Inc.

Marchant, D. C. (2011). Attentional focusing instructions and force production. *Frontiers in Psychology, 26* 10.3389/fpsyg.2010.00210

Marchant, D. C., Carnegie, E., Wood, G., & Ellison, P. (2018). Influence of visual illusion and attentional focusing instructions in motor performance. *International Journal of Sport and Exercise Psychology*.

Marchant, D. C., Clough, P. J., &Crawshaw, M. (2007). The effects of attentional focus strategies on novice dart throwing performance and their task experience. *International Journal of Sport Exercise and Psychology, 5,* 291- 303.

Marchant, D. C., & Greig, M. (2017). Attentional focusing instructions influence quadriceps activity characteristics but not force production during isokinetic knee extensions. *Human Movement Science, 52*, 67-73.

Marchant, D. C., Greig, M., & Scott, C. (2009). Attentional focusing instructions influence force production and muscular activity during isokinetic elbow flexions. *Journal of Strength and Conditioning Research, 23*, 2358-2366.

Masters, R. S. W. (1992). Knowledge, knerves and know-how: The role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. *British Journal of Psychology*, *83*(3), 343–358.

Maxwell, J. P., & Masters, R.S.W. (2002). External versus internal focus instructions: Is the learner paying attention? *International Journal of Applied Sports Sciences*, *14*, 70-88.

Maurer, H., & Zentgraf, K. (2007). On the how and why of the external focus learning advantage. *E-Journal Bewegung und Training, 1*, 31-32.

Maxwell, J. P., & Masters, R. S. W. (2008). The theory of reinvestment. *International Review of Sport and Exercise Psychology, 1*(2), 160-183.

Maxwell, J. P., Masters, R. S. W., Kerr, E., & Weedon, E. (2001). The implicit benefit of learning without errors. *The Quarterly Journal of Experimental Psychology, 54A*(4), 1049-1069.

McKay, B., Lewthwaite, R., & Wulf, G. (2012). Enhanced expectancies improve performance under pressure. *Frontier in Psychology, 25* https://doi.org/10.3389/fpsyg.2012.00008

McKay, B., Wulf, G., Lewthwaite, R., & Nordin, A. (2015). The self: Your own worst enemy? A test of the self-invoking trigger hypothesis. *Quarterly Journal of Experimental Psychology, 68*, 1910-1919.

McCulloch, K. L. (2007). Attention and dual-task conditions: Physical therapy implications for individuals with acquired brain injury. *Journal of Neurology and Physical Therapy,31*, 104-118.

McNevin, N. H., Shea, C. H., & Wulf, G. (2003). Increasing the distance of an external focus of attention enhances learning. *Psychological Research, 67*,22-29.

Meyer, D. E., Abrams, R. A., Kornblum, S., Wright, C. E., & Smith, J. E. K. (1988). Optimality in human motor performance: Ideal control of rapid aimed movements. *Psychological Review, 95*(3), 340-370.

Milton, J. G., Small, S. S., & Solodkin, A. (2004). On the road to automatic: Dynamic aspects in the development of expertise. *Journal of Clinical Neurophysiology, 21*(3), 134-143.

Montesinos, L., Castaldo, R., & Pecchia, L. (2018). On the use of approximate entropy and sample entropy with centre of pressure time-series. *Journal of NeuroEngineering and Rehabilitation, 15*(116), https://doi.org/10.1186/s12984-018-0465-9

Moray, N. (1959). Attention in dichotic listening: Affective cues and the influence of instructions. *Quarterly Journal of Experimental Psychology, 11,* 56-60.

Morgan, W. P., & Pollock, M. L. (1977). Psychologic characterization of the elite distance runner. *Annals of the New York Academy of Science, 301,* 382-403.

Mullen, R., & Hardy, L. (2010). Conscious processing and the process goal paradox. *Journal of Sport & Exercise Psychology, 32*, 275-297.

Newell, K. M. (1991). *Motor skill acquisition. Annual Review of Psychology 42*, 213-237.

Newell, K. M. (1986). Constraints on the development of coordination. In M. G. Wade & H. T. A. Whiting (Eds.). *Motor development in children: Aspects of coordination and control* (pp.341-361). Amsterdam: Nijhoff.

Newell, K. M., Broderick, M. P., Deutsch, K. M., & Slifkin, A. B. (2003). Task goals and change in dynamical degrees of freedom with motor learning. *Journal of Experimental Psychology: Human Perception and Performance, 29*(2), 379-387.

Newell, K. M., Kugler, P. N., van Emmerik, R. E. A., & McDonald, P. V. (1989). Search strategies and the acquisition of coordination. In S. A. Wallace (Ed.), *Advances in psychology, 61. Perspectives on the coordination of movement* (p. 85–122). North-Holland. https://doi.org/10.1016/S0166-4115(08)60019-9

Newell, K. M., & Vaillancourt, D. E. (2001). Dimensional change in motor learning. *Human Movement Science, 20*, 695-715.

Norman, D. A. (1969). Memory while shadowing. *Quarterly Journal of Experimental Psychology, 21*, 85-93.

Oudejans, R. R., Koedijker, J. M., & Beek, P. J. (2007). An outside view on Wulf's external focus: Three recommendation. *E-Journal Bewegung und Training, 1*, 51-52.

Park, S. H., Yi, C. W., Shin, J. Y., & Ryu, Y. U. (2015). Effects of external focus of attention on balance: a short review. *Journal of Physical Therapy Science, 27*(12), 3929.

Perreault, M.E., & French, K. E. (2015). External-focus feedback benefits free-throw learning in children. *Research Quarterly for Exercise and Sport, 86*(4), 422-427.

Prinz, W. (1997). Perception and Action Planning. *European Journal of Cognitive Psychology, 9*(2), 129-154.

Prinz, W. (1992). Why don't we perceive our brain states? *European Journal of Cognitive Psychology, 4*(1), 1-20.

Pohl, P. S., McDowd, J. M., Filion, D., Richards, L. G., & Stiers, W. (2006). Implicit learning of a motor skill after a mild and moderate stroke. *Clinical Rehabilitation, 20,* 246-253.

Poolton, J. M., Maxwell, J. P., Masters, R. S. W., & Raab, M. (2006). Benefits of an external focus of attention: common coding or conscious processing? *Journal of Sports Science, 24*(1), 89-99.

Porter, J. M., & Anton, P. M. (2011). Directing attention externally improves continuous visuomotor skill performance in older adults who have undergone cancer chemotherapy. Journal of American Geriatrics Society, 59(2), 369-370.

Porter, J.M., Anton, P. M. Wikoff, N.M., & Ostrowski, J. B. (2013). Instructing skilled athletes to focus their attention externally at greater distances enhances jumping performance. *Journal of Strength and Conditioning Research, 27*(8), 2073-2078.

Porter, J.M., Anton, P. M. Wikoff, N.M., & Ostrowski, J. B. (2013). Instructing skilled athletes to focus their attention externally at greater distances enhances jumping performance. *Journal of Strength and Conditioning Research, 27*(8), 2073-2078.

Porter, J. M., Nolan, R. P., Ostrowski, E. J., & Wulf, G. (2010a). Directing attentional externally enhances agility performance: A qualitative and quantitative analysis of efficacy of using verbal instructions to focus of attention. *Frontiers in Psychology, 1*, 1- 7.

Porter, J. M., Ostrowski, E. J., Nolan, R. P., & Wu, W. F.W. (2010b). Standing long-jump performance is enhanced when using an external focus of attention. *Journal of Strength and Conditioning Research, 24*(7), 1746-1750.

Porter, J M, & Sims, B. (2013). Altering focus of attention influences elite athletes sprinting performance. *International Journal of Coaching Science*, *7*(2), 41–51.

Potvin-Desrochers, A., Richer, N., & Lajoie, Y. (2017). Cognitive tasks promote automatization of postural control in young and older adults. *Gait & Posture, 57*, 40-45.

Raisbeck, L. D., Yamada, M., & Diekfuss, J. A. (2018). Focus of attention in experienced distance runners. *International Sport Coaching Journal*, *13*(6), 1143-1149.

Raisbeck, L. D., Yamada, M., Diekfuss, J. A., & Kuznetsov, N. A. (2020). The effects of attentional focus instructions and task difficulty in a paced fine motor skill. *Journal of Motor Behavior, 52*(3), 262-270.

Reber, A. S. (1989). Implicit learning and tacit knowledge. *Journal of Experimental Psychology: General, 118*, 219-235.

Reber, A. S. (1967). Implicit learning of artificial grammars. *Journal of Verbal Learning and Verbal Behavior, 77*, 317-327.

Remaud, A., Boyas, S., Lojoie, Y., & Bilodeau, M. (2013). Attentional focus influences postural control and reaction time performances only during challenging dual-task conditions in healthy young adults. *Experimental Brain Research, 231*, 219-229.

Rhea, C. K., Diekfuss, J. A., Fairbrother, J. T., & Raisbeck, L. D. (2019). Postural control entropy is increased when adopting an external focus of attention. *Motor Control, 23*, 230-242.

Rhea, C.K., & Kiefer, A.W. (2014). Patterned variability in gait behavior: How can it be measured and what does it mean? In L. Li, & M. Holmes (Eds.), Gait biometrics: Basic patterns, role of neurological disorders and effects of physical activity. Hauppauge, NY: Nova Science Publishers.

Robertson, E. M. (2007). The serial reaction time task: Implicit motor skill learning? *The Journal of Neuroscience, 27*(38), 10073-10075.

Romaiguere, P. Hasbroucq, T., Possamai, C. & Seal, L. (1993). Intensity to force translation: A new effect of stimulus-response compatibility revealed by analysis of response time and electromyographic activity of a prime mover. *Cognitive Brain Research, 1*, 197-201.

Russell, R., Porter, J. M., & Campbell, O. (2014). An external skill focus is necessary to enhance performance. *Journal of Motor Learning and Development, 2*, 37-46.

Salmoni, A. W., & Mcilwain, J. S. (1979). Fitts' reciprocal tapping task. A measure of motor capacity? *Perceptual and Motor Skills, 49*, 403-413.

Sakurada, T., Hirai, M., & Watanabe, E. (2016). Optimization of motor learning attention-directing strategy based on an individual's motor imagery ability. *Experimental Brain Research, 234*, 301-311.

Sasangohar, F., MacKenzie, S., & Scott, S. D. (2009). Evaluation of mouse and touch input for a tabletop display using Fitts' reciprocal tapping task. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting,* https://doi.org/10.1177/154193120905301216

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82*(4), 225-260.

Schmidt, R. A., Gielen, S. C. A. M., van den Heuvel, P. J. M. (1984). The locus of intersensory facilitation of reaction time. *Acta Psychologica, 57*, 145-164.

Schmidt, R.A., Lee, T.D. (2005). *Motor control and learning: A behavioral emphasis* (4th ed.). Champaign, IL, US: Human Kinetics.

Schmidt, R. A., Zelaznik, H., & Frank, J. S. (1978). Sources of inaccuracy in a rapid movement. In G. E. Stelmach (Ed.), *Information processing in motor control and learning* (pp. 183-203). New York, NY: Academic.

Schmidt, R. A., Zelaznik, H., Hawkins, B., Frank, J. S., & Quinn, H. T. Jr. (1979). Motor-output variability: A theory for the accuracy of rapid motor acts. *Psychological Review, 86*(5), 415-451.

Schneider W, & Shiffrin, R.M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological Review, 84*(1), 1 - 66.

Scholtz, J. P., & Schöner, G. (1999). The uncontrolled manifold concept: Identifying control variables for a functional task. *Experimental Brain Research, 126*, 289-306.

Schomer, H. H. (1986). Mental strategies and the perception of effort of marathon runners. *International Journal of Sport Psychology, 17*, 41-59.

Sharpe, D. (2015). Your chi-square test is statistically significant: Now what? *Practical Assessment, Research & Evaluation, 20*(8), 1-10.

Shea, C. H., & Kohl, R. M. (1991). Composition of practice: Influence on the retention of motor skills. *Research Quarterly for Exercise and Sport, 62*, 187-195.

Sherrington, C. S. (1906). *The integrative action of the nervous system.* New Haven, CT: Yale University Press.

Shuggi, I. M., Oh, H., Shewokis, P. A., & Gentilie, R. J. (2017). Mental workload and motor performance dynamics during practice of reaching movements under various levels of task difficulty. *Neuroscience, 360,* 166-179.

Simon, J. R., & Rudell, A. P. (1967). Auditory S-R compatibility: The effect of an irrelevant cue on information processing. *Journal of Applied Psychology, 51,* 300-304.

Singer, R. N. (1986). Sports Performance: A Five-Step Mental Approach. *Journal of Physical Education, Recreation & Dance, 57*(4), 82–85.

Singer, R. N., Lidor, R., & Cauraugh, J. H. (1993). To be aware or not aware? What to think about while learning and performing a motor skill. *The Sport Psychologist, 7*, 19-30.

Slifkin, A. B., & Newell, K. M. (1999). Noise, information transmission, and force variability. *Journal of Experimental Psychology: Human Perception and Performance, 25*(3), 837-851.

Slifkin, A. B., & Newell, K. M. (1998). Is variability in human performance a reflection of system noise? *Current Directions in Psychological Science*, *7*(6), 170-177.

Smallwood, J., & Schooler, J. W. (2006). The restless mind. *Psychological Bulletin, 132*(6), 946-958.

Smits-Engelsman, B. C. M., Van Galen, G. P., & Duysens, J. (2002). The breakdown of Fitts' law in rapid, reciprocal aiming movements. *Experimental Brain Research, 145*, 222-230.

Snoddy, G. S. (1926). Learning and stability. *Journal of Applied Psychology,10*, 1-36.

Southard, D. (2011). Attentional focus and control parameter: Effect on throwing pattern and performance. *Research Quarterly for Exercise and Sport, 82*(4), 652-666.

Srinivasan, D., Mathiassen, S. E., Samani, A., & Madeliene, P. (2015). The combined influence of task accuracy and pace on motor variability in a standardized repetitive precision. *Ergonomics, 58*(8), 1388-1397.

Stergiou, N., & Decker, L. M. (2010). Human movement variability, nonlinear dynamics, and pathology: Is there a connection? *Human Movement Science, 30*(5), 869–88.

Stoate, W., & Wulf, G. (2011). Does the attentional focus adopted by swimmers affect their performance? *International Journal of Sports and Science & Coaching, 6*, 99-101.

Stratton, S. M., Liu, Y-T., Hong, S. L., Mayer-Kress, G., & Newell, K. M. (2007). Snoddy (1926) revisited: Time scales of motor learning. *Journal of Motor Behavior*, *39*(6), 503-515.

Strayer, D. L., Drews, F. A., & Johnston, W. A. (2003). Cell phone-induced failures of visual attention during simulated driving. *Journal of Experimental Psychology: Applied*, *9*(1), 23-32.

Sullivan, G. M., Feinn, R. Using effect size—or why p-value is not enough. (2012). *Journal of Graduate Medical Education*, *4*(3), 279-282.

Terry, W. S. (2006). Learning and memory. Basic principles, processes, and procedures. Pearson Education, Inc: London, UK.

Thagard, P. (2005). *Mind: Introduction to Cognitive Science.* Cambridge, MA: MIT Press.

Thelen, E. (2005). Dynamic systems theory and the complexity of change. *Psychoanalytic Dialogues*,*15*(2), 255-283.

Thelen, E., & Ulrich, B.D. (1991). Hidden skills: A dynamic systems analysis of treadmill stepping during the first year. *Monographs of the Society for Research in Child Development*, *56*(1), 1–102.

Treisman, A. M. (1964). Selective attention in man. *British Medical Bulletin, 20,* 12-16.

Treisman, A. M. (1960). Contextual cues in selective listening. *Quarterly Journal of Experimental Psychology,12,* 242-248.

Tsao, H., & Hodges, P. W. (2008). Persistence of improvements in postural strategies following motor control training in people with recurrent low back pain. *Journal of Electromyography and Kinesiology, 18*, 559-567.

Vaillancourt, D. E., & Newell, K. M. (2003). Ageing and the time and frequency structure of force output variability. *Journal of Applied Physiology, 94,* 903-912.

Vaillancourt, D. E., & Newell, K. M. (2001). Changing complexity in human behavior and physiology through aging and disease. *Neurobiology of Aging, 23,* 1-11.

Van Orden, G. C., Holden, J. G., & Turvey, M. T. (2005). Human Cognition and 1/f scaling. *Journal of Experimental Psychology: General*, *134*(1), 117-123.

Vance, J., Wulf, G., Tollner, T., McNevin, N., & Mercer J. (2004). EMG activity as a function of the performer's focus of attention. *Journal of Motor Behavior, 36*(4), 450-459.

Varrel, J., Pologe, S., Manselle, W., Lindenberger, U., & Woollacott, M. (2013). Coordination of degrees of freedom and stabilization of task variable in a complex motor skill: Expertise-related differences in cello bowing. *Experimental Brain Research, 224*(3), 323-334.

Vaz, D. V., Avelar, B. S., & Resende, R. A. (2019). Effects of attentional focus on movement coordination complexity. *Human Movement Science, 64*, 171-180.

Veale, J. F. (2014). Edinburgh Handedness Inventory-Short Form: A revised version based on confirmatory factor. *Laterality: Asymmetries of Body, Brain and Cognition, 19*(2), 164-177.

Verejiken, B., van Emmerik, R. E. A., Whiting, H. T. A., & Newell, K. M. (1992). Free(z)ing degrees of freedom in skill acquisition. *Journal of Motor Behavior, 24*(1), 133-142.

Vidal, A., Wu, F.W., Nakajima, M., & Becker, J. (2018). Investigating the constrained action hypothesis: A movement coordination and coordination variability approach. *Journal of Motor Behavior, 50*(5), 528-537.

Wadman, W. J., Denier, van der Gon, J. J., Geuze, R. H., & Mol, C. R. (1979). Control of fast goal-directed arm movements. *Journal of Human Movement Studies*, *5*, 3-17.

Wasserstein, R. L., & Lazar, N. A. (2016). The ASA's statement on p-values: Context, process, and purpose. *The American Statistician*, *70*(2), 129-133.

Welford, A. T. (1952). The "psychological refractory period" and the timing of high-speed performance—a review and a theory. *British Journal of Psychology, 43*, 2-19.

Wijnants, M. L., Bosman, A. M. T., Hasselman, F., Cox, R. F. A., & Van Orden, G. C. (2009). 1/f scaling in movement time changes with practice in precision aiming. *Nonlinear Dynamics, Psychology, and Life Sciences, 13*(1), 75-94.

Wikman, A. Nieminen, T., & Summala, H. (1998). Driving experience and time-sharing during in-car tasks on roads of different width. *Ergonomics, 41*, 358-372.

Winkelman, N. C., Clark, K. P., Ryan, L. J. (2017). Experience level influences the effect of attentional focus on sprint performance. *Human Movement Science, 52,* 84-95.

Wood, N., & Cowan, N. (1995). The cocktail party phenomenon revisited: How frequent are attention shifts to one's name in an irrelevant auditory channel? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21*(1), 255-260.

Woodworth, R. S. (1899). The accuracy of voluntary movement. *Psychological Review, 3*(3, Suppl.13), 1-119.

Wu, W. F. W., Porter, J. M., & Brown, L. E. (2012). Effect of attentional focus strategies on peak force and performance in the standing long jump. *Journal of Strength and Conditioning Research, 26*(5), 1226-1231.

Wu, J., Yang, J., & Honda, T. (2010). Fitts' law holds for pointing movements under conditions of restricted visual feedback. *Human Movement Science, 29,* 882-892.

Wulf, G. (2013). Attentional focus and motor learning: a review of 15 years. *International Review of Sport and Exercise Psychology, 6*(1), 77-104.

Wulf, G. (2007). Methods, findings, explanations, and future directions: Response to commentaries on "attentional focus and motor learning." *E-Journal Bewegung und Training, 1,* 57-64.

Wulf, G., Chiviacowsky, S., & Cardozo, P. (2014). Additive benefits of autonomy support and enhanced expectancies for motor learning. *Human Movement Science, 37*, 12–20. http://dx.doi.org/10.1016/j.humov.2014.06.004.

Wulf, G., Chiviacowsky, S., Schiller, E., Toaldo, L., & Avila, G. (2010). Frequent external-focus feedback enhances motor learning. *Frontiers in Psychology,1*, 1-7.

Wulf, G., Höß, M., & Prinz, W. (1998). Instructions for motor learning: Differential effects of internal versus external focus of attention. *Journal of Motor Behavior*, *30*(2), 169–179.

Wulf, G., Landers, M., Lewthwaite, R., & Tollner, T. (2009). External focus instructions reduce postural instability in individuals with Parkinson's disease. *Physical Therapy, 89*(2), 162 -168.

Wulf, G., Lauterbach, B., & Toole, T. (1999). The learning advantages of an external focus of attention in golf. *Research Quarterly for Exercise and Sport, 70*(2),120-126.

Wulf, G., Lewthwaite, R., Cardozo, P., & Chiviacowsky, S. (2017). Triple play: Additive contributions of enhanced expectancies, autonomy support, and external attentional focus to motor learning. *Quarterly Journal of Experimental Psychology*. http://dx.doi.org/10.1080/17470218.2016.1276204.

Wulf, G., & Lewthwaite, R. (2016). Optimizing performance through intrinsic motivation and attention for learning: The OPTIMAL theory of motor learning. *Psychonomic Bulletin Review, 23*, 1382-1414.

Wulf, G., & Lewthwaite, R. (2010). Effortless motor learning? An external focus of attention enhances movement effectiveness and efficiency. In B. Bruya (Ed.), *Effortless Attention: A New Perspective in Attention and Action* (pp.75-101). Cambridge: MIT Press.

Wulf, G., McConnel, N., Gartner, M., & Schwarz, A. (2002). Enhancing the learning of sport skills through external-focus feedback. *Journal of Motor Behavior, 34*(2), 171-182.

Wulf, G., & McNevin, N. (2003). Simply distracting learners is not enough: More evidence for the learning benefits of an external focus of attention. *European Journal of Sport Science, 3*(5), 1-13.

Wulf, G., McNevin, N. H., Fuchs, T., Ritter, F., & Toole, T. (2000). Attentional focus in complex skill learning. *Research Quarterly for Sport and Exercise*, *71*(3), 229-239.

Wulf, G., McNevin, N., & Shea, C. H. (2001a). The automaticity of complex motor skill learning as a function of attentional focus. *The Quarterly Journal of Experimental Psychology, 54A*(4), 1143-1154.

Wulf, G., & Shea, C. H. (2002). Principles derived from the study of simple skills do not generalize to complex skill learning. *Psychonomic Bulletin & Review, 9*(2), 185-211.

Wulf, G., Shea, C. H., Park, J-H. (2001b). Attention and motor performance: Preferences for and advantages of an external focus. *Research Quarterly for Exercise and Sport*, *72*(4), 335-344.

Wulf, G., & Su, J. (2007). An external focus of attention enhances golf shot accuracy in beginners and experts. *Research Quarterly for Exercise and Sport*, *78*(4), 384-389.

Wulf, G., Töllner, T., & Shea, C.H. (2007). Attentional focus effects as a function of task difficulty. *Research Quarterly of Exercise and Sport, 78*(3), 257–64.

Yamada, M., Diekfuss, J. A., & Raisbeck, L. D. (in press). Motor Behavior Literature Fails to Translate: A preliminary investigation into coaching and focus of attention in recreational distance runners. *International Journal of Exercise and Science.*

Yamada, M., Raisbeck, L. D. (2019, March). *The effects of attentional focus instructions in a speed and accuracy trade-off task on peak velocity and trajectory*. Poster presented at Human Movement Science Symposium at UNC Chapel Hill, NC.

Yamada, M., Raisbeck, L. D., Diekfuss, J. A., Kuznetsov, N. A. (2019). *The effects of attentional focus instructions using Fitts' Law in virtual reality environment.* Manuscript under review.

Yentes, J. M., Hunt, N., Schmid, K. K., Kaipust, J. P., McGrath, D., & Stergiou, N. (2013). The appropriate use of approximate entropy and sample entropy with short data sets. *Annals of Biomedical Engineering, 41*, 341-365.

Yogev-Seligmann, G., Sprecher, E., & Kodesh, E. (2017). The effect of external and internal focus of attention on gait variability in older adults. *Journal of Motor Behavior, 49*(2), 179-184.

Zaal, F. T. J. M., Daigle, K., Gottierb, G. L., & Thelen, E. (1999). An unlearned principle for controlling natural movements. *Journal of Neurophysiology, 82*, 255-259.

Zachry, T., Wulf, G., Mercer, J., & Bezodis, N. (2005). Increased movement accuracy and reduced EMG activity as the result of adopting an external focus of attention. *Brain Research Bulletin, 67,* 304-309.

Zaleznik, H. N., Hawkins, B., & Kisselburgh, L. (1983). Rapid visual feedback processing in single-aiming movements. *Journal of Motor Behavior, 15,* 217-236.

Zarghami, M., Saemi, E., & Fathi, I. (2012). External focus of attention enhances discus throwing performance. *Kinesiology 44*(1),47- 51.

APPENDIX A

INFORMED CONSENT FORM

UNIVERSITY OF NORTH CAROLINA AT GREENSBORO

CONSENT TO ACT AS A HUMAN PARTICIPANT

Project Title: Attention and motor learning in an aiming task.

Principal Investigator: Masahiro Yamada, M.S.
Faculty Advisor: Louisa Raisbeck, Ph. D

What are some general things you should know about research stutdies?
You are being asked to take part in a 3-day research study that separates by 2 days (Mon-Wed-Fri or Tue-Thr-Sat). *Your participation in the study is voluntary*. You may choose not to join, or you may withdraw your consent to be in the study, *for any reason, without penalty*.

Research studies are designed to obtain new knowledge. There may not be any direct benefit to you for being in the research study. There also may be risks to being in research studies. If you choose not to be in the study or leave the study before it is done, it will not affect your relationship with the researcher or the University of North Carolina at Greensboro. It is important that you understand this information so that you can make an informed choice about being in this research study. You will be given a copy of this consent form. If you have any questions about this study at any time, you should ask the researchers.

What is the study about?

This is a research project to investigate various practice methods that may affect motor learning. *Your participation in the study is voluntary*.

Who can participate in this study?

This study is looking for volunteer participants. To participate in this study, you must be over the age of 18 or below 50 and have not participated in this research previously. Also, you must be free from any existing injury, pain or past surgery in the shoulder, arm, and hands.

What will you ask me to do if I agree to be in the study?

During this study, you will complete trials of aiming tasks: Moving an object between two targets back and forth. You are asked to perform the task to the best of your ability based the experimenter's directions. Below is a sequential description of what you will be asked to do.

Day 1 (80 -90 minutes)

Preparation:

1) You will be asked to complete this consent form. If you agree to participate, you will be asked to fill out a demographic form and handedness questionnaire.
2) You will be asked to place special markers to track your arm movements with 3D motion cameras. Then, you will sit in a chair in front of a table and familiarize with the task as described above. Then, 2 physical trials will be collected.
3) You will practice the task to become proficient for the rest of the Day 1. You will also be asked to fill out questionnaires that assess your thoughts during motor performance and mental load. During the questionnaire, your voice will be recorded.
4) You will be asked to revisit the lab for Day 2.

Day 2 (50- 60 minutes)

You will be asked to practice the task. The procedure is the same for Day 1 (2) and (3) except that there will be no familiarization trials. At the end of Day 2, you will perform the task to see the progress.

Day 3 (20-30 minutes)

You will be asked to perform the task to see your progress. On this day, in addition to the (2) of Day 1 part, you will be asked to perform a cognitive task (memory retrieval task) while performing the task. Thus, your voice will be recorded. And, similar to Day 1 and 2, you will be asked to answer some questionnaires about your thoughts.

Will there be any audio/video recording?

Yes. Audio recording will be conducted.

What are the dangers to me?

The Institutional Review Board at the University of North Carolina at Greensboro has determined that participation in this study poses minimal risk to participants. However, some of the questions on the questionnaires may make you feel uncomfortable and you may skip or choose not to answer any question. Physically, there may be a minimal risk of getting soreness. If you have questions, would like more information or have suggestions, please contact Masahiro Yamada at m_yamad2@ uncg.edu or Dr. Louisa Raisbeck at ldraisbe@uncg.edu.

If you have any concerns about your rights, how you are being treated, concerns or complaints about this project or benefits or risks associated with being in this study, please contact the Office of Research Integrity at UNCG toll-free at (855)-251-2351.

Are there any benefits to society?

We believe that the information may be useful in understanding some aspects of human behavior.

Are there any benefits to me?

There are no direct benefits to participants in this study except for the experience you will gain from the participation of this study.

What if I get injured?

We consider there are minimal risks for taking part of this study. However, you might experience a minor muscle soreness or mental fatigue due to practice of the task. UNCG is not able to offer financial compensation nor to absorb the costs of medical treatment should you be injured as a result of participating in this research study. However, we will provide you with a referral to student health or your primary care physician. You do not waive your legal rights by signing this consent form. You may withdraw from participating in this study at any moment if you physically or mentally feel uncomfortable.

Will I get paid for being in the study? Will it cost me anything?

Extra credit may be provided if permitted by your professor/instructor of one of the courses that you are taking. This must be decided prior to the participation of this study. Non-research option will also be available for extra credit. Please ask your instructor. There are no monetary costs to you or made for participating in this study.

How will you keep my information confidential?

All information obtained in this study is strictly confidential unless disclosure is required by law.

Confidentiality will be maintained by means of participant coding. All information obtained from you will be assigned a random number; your name will never be associated with the information obtained (*e.g.*, participant number 4). The researchers listed above will use this number when analyzing, reporting, and (or) summarizing the information obtained from you; your name will never be identified. Additionally, to further maintain your confidentiality; all obtained information (*e.g.*, questionnaires) will remain in a locked file drawer within Dr. Raisbeck's Kinesiology laboratory. Masahiro Yamada will be the only person granted access to the locked file drawer. All electronic data will be stored in UNCG BOX. The information obtained from you will remain in this location for a minimum of five years after the completion of this study and will be destroyed (*i.e.*, shredded) after this time.

Will my de-identified data be used in future studies?

We might use your research in the future studies. These future studies might be done by us or by other investigators. Before we use your data, we will remove information that shows your identity.

What if I want to leave the study?

You have the right to refuse to participate or to withdraw at any time, without penalty. If you do withdraw, it will not affect you in any way. If you choose to withdraw, you may request that any of your data which have been collected be destroyed unless it is in a de-identifiable state. The investigators also have the right to stop your participation at any time. This could be because you have had an unexpected reaction, or have failed to follow instructions, or because the entire study has been stopped.

What about new information/changes in the study?

If significant new information relating to the study becomes available which may relate to your willingness to continue to participate, this information will be provided to you.

Voluntary consent by participant:

By signing this consent form you are agreeing that you have read, or it has been read to you, and you fully understand the contents of this document and are giving us your openly willing consent to take part in this study. All of your questions concerning this study have been answered. By signing this form, you are agreeing that you are 18 years of age or older and are agreeing to participate, or have the individual specified above as a participant, in this study described to you

by Masahiro Yamada. Data ________________

Your name: ___________________________

Signature: ____________________________ Date:_________________

APPENDIX B

FLYERS

RESEARCH PARTICIPANTS NEEDED!

Attention and Motor Learning in an Aiming Task.

Principal Investigators: Masahiro Yamada, M.S.

Academic Advisor: Louisa Raisbeck, Ph.D

WHAT IS THIS STUDY ABOUT?

This study examines the effect of verbal instructions in an aiming task. You will be asked to move an object between two targets back and forth and perform as fast and accurately as possible. Your goal is to increase accuracy and movement speed. We will investigate performance, movement coordination, and your cognitive process using questionnaires. The consent form, demographics (height, weight, age, gender), and eligibility (injury, previous research participation) will be asked to fill out. Your performance will be collected via 3D motion capture cameras. During data collection, you will be asked to answer questionnaires about your thoughts and mental load. The participation and retrieval from participation are voluntary at any moment if you feel uncomfortable.

ELIGIBILITY

To participant in this study, you must:

(1) Be older than 18 years old and younger than 50 years old,
(2) Be free from injuries/pain in the arms, hands, and fingers;
(3) Have never participated in a similar study.

DURATION

- 3 separate-day participation study (Mon-Wed-Fri or Tue-Thr-Sat).
- Day 1 will take 80-90 min., Day 2 will take 50-60 min., and Day 3 will take 20-30 min.

LOCATION

- The location is the Virtual Environment and Assessment Rehabilitation (VEAR) lab (Coleman 247).

COMPENSATION

- There is *no* compensation for participating in this study.
- *Extra credits may be offered for research participation from your course instructor*. Please check with your instructor *prior to* participation. If you're interested in an alternative method to receive extra credits, please ask your instructor.

For more information or appointment:

m_yamad2@uncg.edu

APPENDIX C

ORAL RECRUITMENT SCRIPT

Hi, my name is Masahiro Yamada (or other research assistant listed); I am a doctoral student assisting for the department of Kinesiology. We are looking for voluntary participation in our study. This research examines the effect of verbal instructions in an aiming task. You will be asked to sit in a chair and move an object between targets based on a provided instruction while your movements are recorded through 3-D motion analysis. You will also be asked to answer questionnaires. While this study may not directly benefit you except for the experience, it may help further our understanding of human behavior in learning motor skills. This is a 3-day participation study that separates by 2 days (M-W-F or T-R-S). The first two days will be practice, and you will be tested on day 3. The first day takes about 80 minutes, second day will be about 60 minutes, and the third day takes about 20 minutes. The participation criteria are that 1) you are over 18 years or younger than 50 years old, 2) no existing injury or pain in your arms or hands, no history of surgery in the arms or hands, 3) never participated in this study. All experimental procedure is held at the VEAR lab (Coleman 247). If you are interested in participating in the study, please email me to make an appointment. There will be no direct benefit to you or monetary incentives. If your instructor offers extra credit opportunity for research participation, you may use that opportunity for this study. If you decide not to participate, you will have an alternative. Please ask your instructor About the extra credits.

APPENDIX D

DEMOGRAPHIC FORM

SUBJECT DEMOGRAPHICS

Sex ________________

Age ________________

Height (ft & in) ________________

Mass (lbs) ________________

HEALTH HISTORY

Do you have any General Health Problems or Illnesses? (*e.g.* diabetes, respiratory disease)
Yes____ No____ If Yes, please specify____

Do you have any history of connective tissue injury, disease or disorders? (*e.g.*, Rheumatoid Arthritis, tendinitis, fracture) Yes____ No____

If Yes, please specify____

Please list any medications you take regularly: ____

____

Please list any previous surgery to your upper extremities (Include a description of the surgery, the date of the surgery, and whether it was on the left or right side)

Body Part Description Date of Surgery Side (L or R)

____

____

____

____

Have you participated in a study, using the similar task that is described in the consent form?

Yes/ No

APPENDIX E

THE EDINBURGH HANDEDNESS INVENTORY-SHORT FORM

Please indicate your preferences in the use of hands in the following activities or objects:

Always right Usually right Both Equally

Usually left Always left

Writing:

Throwing:

Toothbrush:

Spoon:

Scoring:

For each item: Always right = 100; Usually right = 50; Both equally = 0; Usually left = -50;

Always left = -100

To calculate the Laterality Quotient add the scores for the four items in the scale and divide

this by four:

Writing score _____________

Throwing score_____________

Toothbrush score_____________

Spoon score_____________

Total_____________

Total ÷ 4 (Laterality Quotient) _____________

Classification: Laterality Quotient score:

Left handers -100 to -61

Mixed handers -60 to 60

Right handers 61 to 100

APPENDIX F

PERCEIVED COMPENTENCE QUESTIONNAIRE

“How well do you think you will perform on the follow-up task?”

Please answer out of 7-point Likert Scale.

1 = very poor and 7 = very well

APPENDIX G

NASA-TLX FORM

How mentally demanding was the task?

Very Low Very High

How physically demanding was the task?

Very Low Very High

How hurried or rushed was the pace of the task?

Very Low Very High

How successful were you in accomplishing
what you were asked to do?

Perfect Failure

How hard did you have to work to
accomplish your level of performance?

Very Low Very High

How insecure, discouraged, irritated,
stressed, and annoyed were you?

Very Low Very High

APPENDIX H

VERBAL INSTRUCTIONS

For EXF:

Mentally focus on moving the pen as fast and accurately as possible.

For INF:

Mentally focus on moving your hand as fast and accurately as possible.

For CON:

I want you to only think about doing your best.

APPENDIX I

COMPLIANCE CHECK AND EXPLICIT KNOWLEDGE FORM

1) What was the instruction(s) (provided in a paper form)?

2) On a scale of 1-7, how much were you able to follow the instruction given in the (2) while performing the task? Please circle one.

1 2 3 4
5 6 7

Don't remember Sometimes A third of A half of Most of Almost always
Always

the times the times the times

3) (Explicit knowledge question) In addition to the given instruction in 1), if there were any methods, techniques that you adopted, or any thoughts that are not related to the task, please report. If you weren't thinking about anything else, you do not have to answer the question.

APPENDIX J

MT AND TAP ERRORS IN THE ACQUISITION PHASE

The mean (SD) of MT during the Acquisition Phase.

		Block 1	Block 2	Block 3	Block 4
INF	ID_{low}	375.41 (94.07)	354.83 (85.39)	342.84 (62.44)	333.80 (63.35)
	ID_{med}	558.97 (98.85)	547.22 (89.30)	536.49 (82.80)	541.43 (57.76)
	ID_{high}	1057.72 (138.75)	1035.19 (118.85)	1031.90 (115.38)	1042.94 (144.37)
EXF	ID_{low}	421.74 (86.71)	390.77 (77.10)	376.01 (74.20)	350.91 (67.50)
	ID_{med}	563.69 (82.88)	580.36 (95.21)	553.36 (82.76)	555.51 (78.74)
	ID_{high}	1083.43 (138.75)	1104.15 (275.32)	1026.15 (183.96)	1008.10 (154.05)
CON	ID_{low}	392.27 (61.22)	368.45 (55.64)	382.51 (61.93)	353.71 (54.36)
	ID_{med}	590.13 (57.65)	565.78 (61.29)	583.09 (64.64)	564.22 (58.72)
	ID_{high}	1127.90 (199.28)	1076.60 (209.16)	1122.21 (259.93)	1055.09 (270.51)

The mean (SD) of Error Taps during the Acquisition Phase.

		Block 1	Block 2	Block 3	Block 4
INF	ID_{low}	0.15 (0.37)	0.20 (0.49)	0.20 (0.31)	0.30 (0.57)
	ID_{med}	1.95 (1.32)	1.60 (1.23)	1.50 (1.43)	1.80 (1.20)
	ID_{high}	6.00 (2.08)	6.00 (2.36)	6.10 (2.77)	4.80 (2.12)
EXF	ID_{low}	0.15 (0.49)	0.15 (0.37)	0.10 (0.22)	0.10 (0.31)
	ID_{med}	1.40 (1.35)	1.15 (1.18)	1.00 (1.03)	1.15 (1.18)
	ID_{high}	5.60 (2.60)	5.10 (2.85)	4.55 (2.50)	4.70 (2.36)
CON	ID_{low}	0.10 (0.31)	0.15 (0.42)	0.05 (0.37)	0.05 (0.22)
	ID_{med}	1.45 (1.15)	1.15 (1.09)	1.30 (1.17)	1.15 (1.22)
	ID_{high}	4.85 (2.48)	5.10 (2.15)	4.30 (2.68)	4.45 (2.44)

APPENDIX K

DETAIL OF THE STATISTICAL RESULTS OF CHAPTER IV

F-scores and effect size of the main analyses of MT

	Factor	DOF	F-score	p-value	partial eta squared	Effect size Interpretation
Baseline to Retention tests	ID	1.13, 64.26	749.92	< .01*	0.93	Large
	ID x Group	2.26, 64.26	0.58	> .05	0.02	Small
	Time	1.45, 82.80	54.99	< .01*	0.50	Large
	Time x Group	2.91, 82.80	1.87	> .05	0.06	Medium
	ID x Time	1.65, 93.80	4.94	<. 01*	0.08	Medium
	3-way Int	3.30, 93.80	1.18	> .05	0.04	Small
	Group	2, 57	0.34	> .05	0.01	N/A
DTC (Transfer test)	ID	1.73, 98.67	10.51	<. 01*	0.16	Large
	ID x Group	3.47, 98.67	1.19	> .05	0.04	Small
	Group	2,57	0.2	> .05	< .01	N/A

Note. DOF = degrees of freedom, 3-way Int = 3 way interaction; Statistical analysis were repeated measures of ANOVA between baseline and two retention tests and DTC (Dual Task Cost) = 3 (Group) x 3 (ID); effect size interpretation is based on Cohen (1988). * indicates significant results, $p < .05$.

F-scores and effect size of the main analyses of error taps

	Factor	DOF	F-score	p-value	partial eta squared	Effect size Interpretation
Baseline to retention tests	ID	1.41, 80.33	396.52	< .01*	0.87	Medium
	ID x Group	2.82, 80.33	0.28	> .05	0.02	N/A
	Time	2, 114	5.2	< .01*	0.08	Medium
	Time x Group	4, 114	0.44	> .05	0.02	Small
	ID x Time	2.66, 151.76	7	<. 01*	0.11	Medium
	3-way Int	5.33, 151.76	1.86	> .05	0.06	Medium
	Group	2, 57	0.68	> .05	0.02	Small
Transfer test	ID	1.33, 75.51	123.19	<. 01*	0.69	Large
	ID x Group	2.65, 75.51	1.79	> .05	0.06	Medium
	Group	2, 57	3.1	= .053	0.1	Medium

APPENDIX L

THE RESULTS OF PRECISE ACCURACY (MRE AND BVE)

Statistical results of MRE

	Factor	DOF	F-score	p-value	partial eta squared	Effect size Interpretation
Baseline to retention	ID	1.76, 100.07	4.83	< .05*	0.08	Medium
	ID x Group	3.51, 100.07	0.34	>.05	0.01	Small
	Time	1.18, 101.37	3.91	< .05*	0.06	Medium
	Time x Group	3.58, 101.37	0.84	> .05	0.03	Small
	ID x Time	2.30, 130.63	2.23	> .05	0.04	Small
	3-way Int	4.58, 130.63	0.77	> .05	0.03	Small
	Group	2, 57	0.52	> .05	0.02	Small
Transfer	ID	1.52, 86.73	3.82	< .05*	0.06	Medium
	ID x Group	3.04, 86.73	1.79	> .05	0.06	Medium
	Group	2,57	0.38	> .05	0.02	Small

Mean (SD) of MRE

		Base	5-min Ret	48-h Ret	Transfer
INF	ID_{low}	15.31 (3.47)	15.20 (4.74)	15.23 (3.98)	15.30 (.91)
	ID_{med}	15.71 (3.40)	17.57 (6.44)	15.78 (4.13)	14.85 (1.41)
	ID_{high}	15.13 (3.78)	14.87 (5.54)	14.86 (4.37)	14.93 (0.94)
EXF	ID_{low}	16.32 (2.94)	15.71 (3.36)	15.30 (3.28)	16.35 (0.91)
	ID_{med}	16.37 (2.97)	17.54 (6.18)	16.40 (5.86)	16.80 (1.41)
	ID_{high}	16.35 (3.07)	16.72 (4.55)	15.56 (3.17)	15.43 (0.94)
CON	ID_{low}	15.10 (3.73)	14.35 (5.00)	14.02 (4.56)	14.58 (0.91)
	ID_{med}	14.84 (4.49)	16.11 (6.35)	14.77 (7.98)	16.88 (1.41)
	ID_{high}	14.44 (5.11)	16.75 (4.39)	14.75 (4.36)	13.69 (0.94)

Statistical results of BVE

	Factor	DOF	F-score	p-value	partial eta squared	Effect size Interpretation
Baseline	ID	1.50, 85.59	176.48	$< .01$*	0.76	Large
to retention	ID x Group	3.00, 85.59	1.88	$>.05$	0.06	Medium
	Time	1.78, 101.29	6.17	$< .01$*	0.1	Medium
	Time x Group	3.55, 101.29	1.78	$> .05$	0.06	Medium
	ID x Time	2.97, 169.22	2.67	$< .05$*	0.05	Small
	3-way Int	5.94, 169.22	1.08	$> .05$	0.04	Small
	Group	2,57	1.2	$> .05$	0.04	Small
Transfer	ID	1.60, 91.14	148.59	$< .01$*	0.72	Large
	ID x Group	3.20, 91.14	1.75	$> .05$	0.06	Medium
	Group	2, 57	3.46	$< .05$*	0.11	Medium

Mean (SD) of BVE

		Base	5-min Ret	48-h Ret	Transfer
INF	ID_{low}	3.62(1.31)	4.16(0.95)	4.30 (0.85)	4.24 (0.70)
	ID_{med}	3.00 (0.92)	3.38 (0.53)	3.34 (0.6)	3.40 (0.61)
	ID_{high}	2.04 (0.34)	2.20 (0.40)	2.18 (0.43)	2.22 (0.34)
EXF	ID_{low}	3.23 (0.77)	3.76 (0.93)	3.92 (0.92)	3.80 (1.07)
	ID_{med}	3.06 (0.61)	3.055 (0.56)	3.17 (0.70)	2.98 (0.53)
	ID_{high}	2.20 (0.44)	2.15 (0.44)	2.49 (1.49)	2.26 (0.35)
CON	ID_{low}	3.56 (0.82)	3.67 (0.98)	3.55 (0.80)	3.60 (0.85)
	ID_{med}	3.16 (0.45)	3.10 (0.47)	3.11 (0.43)	3.02 (0.64)
	ID_{high}	2.02 (0.32)	2.11 (0.30)	2.09 (0.35)	2.07 (0.45)

APPENDIX M

STATISTICAL RESULTS OF JOINT ANGULAR VELOCITY

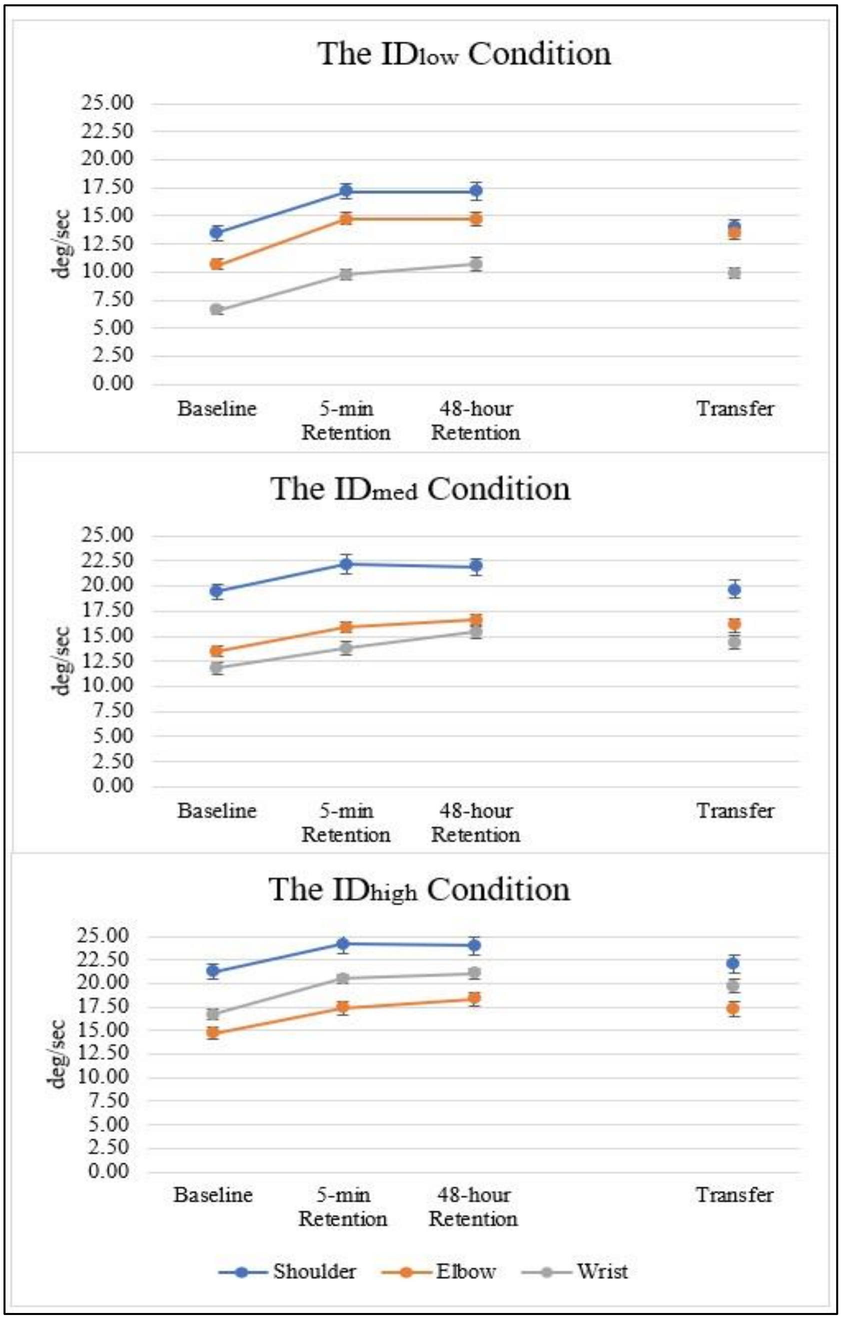
Statistical results of the mean angular velocity

	DOF	F-score	p-value	Partial eta squared	Effect size Interpretation
ID	1.20	169.17	< .01*	0.75	Medium
ID x Group	2.41	0.45	0.67	0.02	Small
Error	68.68				
Time	1.40	72.27	< .01*	0.56	Large
Time x Group	2.80	2.82	0.05*	0.09	Medium
Error	79.86				
Joint	1.78	47.10	< .01*	0.45	Large
Joint x Group	3.56	1.90	0.12	0.06	Medium
Error	101.33				
ID X Time	3.41	2.31	0.07*	0.04	Small
ID x Time x Group	6.81	0.63	0.72	0.02	Small
Error	194.21				
ID x Joint	2.88	45.69	< .01*	0.44	Large
ID x Joint x Group	5.77	2.11	0.06	0.07	Medium
Error	164.42				
Time x Joint	2.90	1.50	0.22	0.03	Small
Time x Joint x Group	5.80	0.64	0.70	0.02	Small
Error	165.41				
ID x Time x Joint	5.66	1.63	0.14	0.03	Small
ID x Time x Joint x Group	11.32	0.59	0.84	0.02	Small
Error	322.66				
Group	2.00	0.74	0.48	0.03	Small
Error	57.00				

Statistical results of the mean angular velocity (transfer test)

	DOF	F-score	p-value	Partial Eta Squared	Interpretation of Effect size
ID	1.26	114.18	< .01	0.67	Large
ID x Group	2.52	0.50	0.652	0.02	Small
Error	71.73				
Joint	2.00	7.35	< .01	0.21	Large
Joint x Group	4.00	0.97	0.43	0.03	Small
Error	114.00				
ID x Joint	3.18	20.31	< .01	0.26	Large
ID x Joint x Group	6.35	0.61	0.73	0.02	Small
Error	181.08				
Group	2	0.80	0.46	0.03	Small
Error	57				

Mean angular velocity over time



APPENDIX N

DETAIL OF THE STATISTICAL RESULTS OF CHAPTER V

Statistical results of the SD angular velocity (Baseline to Retention tests)

	DOF	F-score	p-value	Partial Eta Squared	Effect Size Interpretation
ID	1.32	814.16	0.00	0.93	Large
ID x Group	2.64	0.25	0.84	0.01	Small
Error	75.19				
Time	1.46	29.78	0.00	0.34	Large
Time x Group	2.91	1.44	0.24	0.05	Small
Error	83.03				
Joint	2.00	16.34	0.00	0.22	Large
Joint x Group	4.00	1.95	0.11	0.06	Medium
Error	114.00				
ID x Time	3.33	2.54	0.05	0.04	Small
ID x Time x Group	6.65	0.17	0.99	0.01	Small
Error	189.54				
ID x Joint	2.33	55.21	0.00	0.49	Large
ID x Joint x Group	4.67	1.25	0.29	0.04	Small
Error	133.03				
Time x Joint	2.93	7.96	0.00	0.12	Medium
Time x Joint x Group	5.86	0.51	0.79	0.02	Small
Error	166.97				
ID x Time x Joint	4.54	1.57	0.17	0.03	Small
ID x Time x Joint x Group	9.07	0.36	0.96	0.01	Small
Error	258.58				
Group	2.00	0.87	0.42	0.03	Small
Error	57.00				

Statistical results of SD of angular velocity during the transfer test

	DOF	F-score	p-value	Partial Eta Squared	Effect Size Interpretation
ID	1.00	6.94	< .01*	0.11	Medium
ID x Group	2.00	0.99	0.38	0.03	Small
Error	57.14				
Joint	1.01	0.94	0.34	0.02	Small
Joint x Group	2.03	1.11	0.34	0.04	Small
Error	57.14				
ID x Joint	1.00	1.39	0.24	0.02	Small
ID x Joint x Group	2.01	0.99	0.38	0.03	Small
Error	57.17				
Group	2	0.93	0.40	0.03	Small
Error	57				

Statistical results of the CV angular velocity (Baseline to Retention tests)

	DOF	F-score	p-value	Partial Eta Squared	Effect Size Interpretation
ID	1.40, 79.88	588.01	< .01*	0.91	Medium
ID x Groups	2.80, 79.88	0.67	0.56	0.02	Small
Time	1.38, 78.66	53.59	< .01*	0.48	Small
Time x Group	2.76, 78.66	1.00	0.39	0.03	Small
joint by group	1.76, 100.42	149.23	< .01*	0.72	Medium
Joint by Group	3.52, 100.42	0.73	0.55	0.03	Small
ID x Time	2.52, 143.39	3.12	< .05*	0.05	Small
ID x Time x Group	5.03, 143.39	0.67	0.65	0.02	Small
ID x Joint	2.78, 158.49	52.52	< .01*	0.48	Small
ID x Joint x Group	5.56, 158.49	0.61	0.71	0.02	Small
Time x Joint	2.33, 133.09	14.04	< .01*	0.20	Large
Time x Joint x Group	4.67, 133.09	0.36	0.86	0.01	Small
Time x ID x Joint	4.83, 275.20	1.72	0.13	0.03	Small
Time x ID x Joint x Group	9.66, 275.20	1.47	0.15	0.05	Small
Group	2, 57	0.08	0.93	0.00	N/A

Statistical results of CV of angular velocity during the transfer test

ID	1.08, 61.56	81.8	< .01*	0.59	Small
ID x Group	2.16, 61.56	0.77	> .05	0.03	Small
Joint	1.05, 59.79	13.95	< .01*	0.2	Small
Joint x Group	2.10, 59.79	0.42	> .05	0.01	Small
ID x Joint	1.04, 59.35	1.67	> .05	0.03	Small
ID x Joint x Group	2.08, 59.35	1	> .05	0.03	Small
Group	2, 57	2.17	> .05	0.07	Medium

Statistical results of the SampEn of angular velocity (Baseline to Retention tests)

	DOF	F-score	p-value	Partial Eta Squared	Effect Size Interpretation
ID	1.82	15.36	< .01*	0.21	Large
ID x Group	4.00	1.62	0.18	0.05	Small
Error	103.64				
Time	1.60	696.40	< .01*	0.92	Medium
Time x Group	3.19	0.22	0.89	0.01	Small
Error	91.00				
Joint	2.00	423.06	< .01*	0.88	Large
Joint x Group	4.00	2.56	< .05*	0.08	Medium
Error	114.00				
ID x Time	4.00	1.65	0.16	0.03	Small
ID x Time x Group	8.00	0.79	0.61	0.03	Small
Error	228.00				
ID x Joint	3.14	4.15	< .01*	0.07	Medium
ID x Joint x Group	6.27	0.48	0.83	0.02	Small
Error	178.71				
Time x Joint	3.19	97.53	< .01*	0.63	Large
Time x Joint x Group	6.38	2.54	< .05*	0.08	Medium
Error	181.89				
ID x Time x Joint	5.10	3.70	< .01*	0.06	Medium
ID x Time x Joint x Group	10.19	1.65	0.09	0.05	Small
Error	290.42				
Group	2.00	0.96	0.39	0.03	Small
Error	57.00				

Statistical results of SampEn of angular velocity during the transfer test

	DOF	F-score	p-value	Partial Eta Squared	Effect Size Interpretation
ID	1.36	115.14	< .01*	0.67	Large
ID x Group	2.73	1.37	0.26	0.05	Small
Error	77.72				
Joint	1.64	147.22	< .01*	0.72	Large
Joint x Group	3.28	0.78	0.52	0.03	Small
Error	93.62				
ID x Joint	1.57	13.01	< .01*	0.19	Large
ID x Joint x Group	3.14	0.74	0.54	0.03	Small
Error	89.62				
Group	2.00	0.64	0.53	0.02	Small
Error	57.00				

APPENDIX O

DETAIL OF THE STATISTICAL RESULTS OF CHAPTER VI

Statistical results and effect size of the NASA-TLX

	Factor	DOF	F-score	p-value	partial eta squared	Effect size Interpretation
Baseline	ID	1.40, 79.68	89.79	< .01*	0.61	Large
	ID x Group	2.80, 79.68	1.54	>. 05	0.05	Small
	Group	2,57	0.24	> .05	<. 01	N/A
Practice	ID	1.24, 70.77	95.87	< .01*	0.63	Large
	ID x Group	2.47, 70.37	0.3	>.05	< 0.01	N/A
	Time	2.17, 123.68	40.56	< .01*	0.42	Large
	Time x Group	4.34, 123.68	0.56	> .05	< 0.01	N/A
	ID x Time	4.60, 261.92	2.03	> .05	0.03	Small
	3-way Int	9.19, 261.92	0.53	> .05	< 0.01	N/A
	Group	2,57	0.57	> .05	< 0.01	N/A
Retention	ID	2, 114	100.54	< .01*	0.64	Large
	ID x Group	4, 114	0.15	> .05	< 0.01	N/A
	Time	1, 57	13.68	< .01*	0.19	Large
	Time x Group	2, 57	0.12	> .05	< .01	N/A
	ID x Time	2, 114	1.89	> .05	0.03	Small
	3-way Int	4, 114	0.12	> .05	< .01	N/A
	Group	2, 57	0.02	> .05	< .01	N/A
Transfer	ID	1.72, 97.77	2.72	> .05	0.05	Small
	ID x Group	3.43, 97.77	0.55	> .05	< 0.01	N/A
	Group	2, 57	0.05	> .05	< 0.01	N/A

Note. DOF = degrees of freedom, Statistical analyses were repeated measures of ANOVA for Baseline = 3 (Group) x 3 (ID); Practice = 3 (Group) x 3 (ID) x 4 (Time); Retention = 3 (Group) x 3 (ID) x 2 (Time); Transfer = 3 (Group) x 3 (ID); effect size interpretation is based on Cohen (1988); 3-way Int = 3-way interaction.; * indicates a significant effect.

Statistical results and effect size of the amount of explicit knowledge.

	Factor	DOF	F-score	p-value	partial eta squared	Effect size Interpretation
Practice	ID	2,114	7.78	<. 01*	0.12	Medium
	ID x Group	4,114	1.6	> .05	0.05	Small
	Time	3,171	17.19	<. 01*	0.23	Large
	Time X Group	6,171	0.95	> .05	0.03	Small
	ID x Time	6,342	1.25	> .05	0.02	Small
	3-way Int	12,342	0.84	> .05	0.03	Small
	Group	2,57	0.03	> 0.5	<. 01	N/A
Retention	ID	1.69,96.00	13.75	<. 01*	0.19	Large
	ID x Group	3.37, 96.00	2.83	<. 05*	0.09	Medium
	Time	1,57	< .1	> .05	<. 01	N/A
	Time X Group	2,57	1.81	>. 05	0.06	Medium
	ID x Time	2,114	2.02	>. 05	0.03	Small
	3-way Int	4,114	0.52	> .05	0.02	Small
	Group	2,57	0.99	> .05	0.03	Small
Transfer	ID	2,114	3.36	<. 05*	0.06	Medium
	ID x Group	4,114	1.4	>. 05	0.05	Small
	Group	2,57	1.05	> .05	0.04	Small

Note. DOF = degrees of freedom, Statistical analyses were repeated measures of ANOVA for Practice = 3 (Group) x 3 (ID) x 4 (Time); Retention = 3 (Group) x 3 (ID) x 2 (Time); Transfer = 3 (Group) x 3 (ID); effect size interpretation is based on Cohen (1988); 3-way Int = 3-way interaction.; * indicates a significant effect.

Statistical results and effect size of perceived competence.

	Factor	DOF	F-score	p-value	partial eta squared	Effect size Interpretation
Baseline	ID	1.72, 98.00	25.46	< .01*	0.31	Large
	ID x Group	3.44, 98.00	0.33	> .05	0.01	Small
	Group	2, 57	0.15	> .05	< .01	N/A
Practice	ID	1.75, 99.01	413.33	< .01*	0.88	Large
	ID x Group	3.51, 99.01	1.85	> .05	0.06	Medium
	Time	2.50, 142.35	39.78	<. 01*	0.41	Large
	Time x Group	5.00, 142.35	1.07	> .05	0.04	Small
	ID x Time	5.02, 286.02	1.04	> .05	0.02	Small
	3-way Int	10.04, 286.02	0.92	> .05	0.03	Small
	Group	2, 57	0.39	> .05	0.01	N/A
Retention	ID	1.60, 91.30	275.35	< .01*	0.83	Large
	ID x Group	3.20,91.30	0.42	> .05	0.02	Small
	Time	1, 57	2.66	>.05	0.05	Small
	Time x Group	2, 57	0.16	> .05	< .01	N/A
	ID x Time	2, 114	0.76	> .05	0.01	Small
	3-way Int	4, 114	0.34	> .05	0.01	Small
	Group	2, 57	0.02	> .05	< .01	N/A
Transfer	ID	1.71, 97.60	85.29	<. 01*	0.6	Large
	ID x Group	3.42, 97.60	0.82	> .05	0.03	Small
	Group	2,57	0.08	> .05	< .01	N/A

Note. DOF = degrees of freedom, Statistical analyses were repeated measures of ANOVA for Baseline = 3 (Group) x 3 (ID); Practice = 3 (Group) x 3 (ID) x 4 (Time); Retention = 3 (Group) x 3 (ID) x 2 (Time); Transfer = 3 (Group) x 3 (ID); effect size interpretation is based on Cohen (1988); 3-way Int = 3-way interaction.; * indicates a significant effect.

Statistical results and effect size of the magnitude of compliance.

	Factor	DOF	F-score	p-value	partial eta squared	Effect size Interpretation
Practice	ID	1.56,88.81	58.84	< .01*	0.51	Large
	ID x Group	3.12, 88.81	3.92	<. 05*	0.12	Large
	Time	2.11, 120.18	12.65	< .01*	0.18	Large
	Time x Group	4.22,12.18	2.05	> .05	0.07	Medium
	ID x Time	3.62, 206.45	3.45	< .05*	0.06	Medium
	3-way Int	7.24, 206.45	1.45	> .05	0.05	Small
	Group	2, 57	8.32	< .01*	0.23	Large
Retention	ID	1.62, 92.59	49.89	<. 01*	0.47	Large
	ID x Group	3.25, 92.59	5.05	<. 01*	0.15	Large
	Time	1, 57	1.85	> .05	0.03	Small
	Time x Group	2, 57	1.71	> .05	0.04	Small
	ID x Time	2, 114	0.47	> .05	< .01	N/A
	3-way Int	4, 114	2.6	< .05*	0.08	Medium
	Group	2, 57	3.1	> .05	0.1	Medium
Transfer	ID	1.81, 103.32	7.72	< .01*	0.12	Large
	ID x Group	3.63, 103.32	3.35	< .05*	0.11	Medium
	Group	2, 57	1.79	> .05	0.06	Medium

Note. DOF = degrees of freedom, Statistical analyses were repeated measures of ANOVA for Practice = 3 (Group) x 3 (ID) x 4 (Time); Retention = 3 (Group) x 3 (ID) x 2 (Time); Transfer = 3 (Group) x 3 (ID); effect size interpretation is based on Cohen (1988); 3-way Int = 3-way interaction.; * indicates a significant effect.